The Blashke Island ultrabasic complex
with notes on related areas in southeastern Alaska

by

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Abstract

The Blashke Island complex described in detail and two other complexes treated briefly are 3 of at least 8 well-defined ultrabasic intrusive masses in southeastern Alaska, each of which contains all or parts of a genetically related sequence of basic to ultrabasic rocks including dunite, pyroxenite, hornblendite, and gabbro with gradational facies and minor variants. These complexes are emplaced in a variety of terrains, including both Paleozoic and Mesozoic rocks, all of which have undergone deformation and igneous intrusion during a late Jurassic or early Cretaceous orogeny culminating in the emplacement of the Coast Range batholith. The ultrabasic intrusions are correlated with the earliest phases of intrusive activity and antedate the more silicic and alkalic intrusions.

The Blashke Island complex consists of a nearly circular core of dunite 6,000 feet to 9,000 feet in diameter encircled by a ring of olivine augitite from a few hundred to 1,500 feet wide, outside of which is a nearly complete ring of gabbro, locally absent and ranging up to [illegible] feet wide.

Most of the dunite core contains only chromite and olivine as primary phases. Near the margin augite is present as a late primary phase and the rock passes into augite dunite or wehrlite. The olivine augitite ring contains essentially only augite and olivine, but near its outer margin a little anorthite and hornblende are present sporadically as late primary phases. The gabbro is irregular in composition and texture, but tends to pass from an olivine-augite gabbro near its inner contact with olivine augitite into a hornblende gabbro near the outer margins where it is wide.

Well-defined dikes up to a foot wide of augite dunite and wehrlite cut both the dunite and the olivine augitite and thin dikes of augitite cut marginal parts of the dunite core.

Near the outer margin of the olivine augitite ring there are small, irregular masses and well-defined dikes of coarse gabbroic pegmatite consisting of coarse anorthite, augite, olivine, hornblende, and accessories.

A group of dikes, here called beerbachite, ranging from olivine gabbro to hornblendite in composition and characterized by aplitic texture, cut the olivine augitite and gabbro. Inclusions of country rock in the olivine augitite and gabbro correspond closely to the hornblende beerbachite dikes in texture and composition. One unusual dike-like rock, cross-cutting olivine augitite and associated with beerbachite dikes, consists mainly of diopsidic augite and andradite garnet.

Within a couple of thousand feet of the complex there are a number of dikes and irregular masses of gabbro similar to that in the complex. The country rocks throughout the islands are also cut by numerous dikes of gabbroic to andesitic composition, generally with porphyritic and ophitic or diabasic textures that are metamorphosed by and antedate the complex. Later dikes of andesite-basalt melaphyre cut the complex and are correlated with Tertiary dikes in the region.

The country rocks invaded by the complex consist of lower and middle Ordovician graywacke, and conglomerate, and a lower Silurian sequence containing much conglomerate, graywacke, slate, some limestone, and much andesitic pyroclastic material. A younger Silurian sequence that is largely limestone is unconformable with the older rocks and outcrops at the north end of the islands over a mile from the complex. All the Ordovician rocks and the rocks of the lower Silurian sequence underwent low grade regional metamorphism and some folding before the laying down of the younger Silurian rocks. Within 100 feet or more of the complex all country rocks irrespective of original composition have been converted into granulite of gabbroic composition. The intensity of contact metamorphism diminishes with distance from the complex and becomes negligible within several hundred to a thousand feet.

The contacts between the several rock units of the complex and between the complex and surrounding rocks are irregular in detail but essentially steep. The complex is a nearly cylindrical plug, but may have passed into a dome-like structure a short distance above the present level of exposure. The enclosing rocks have been folded regionally and are part of a major structure called the Kashevarof anticlinorium. The complex is strongly transgressive, cutting across structures in the enclosing rocks, but also has had a doming or upward-dragging effect on the enclosing rocks. Ordovician rocks crop out around the complex and not elsewhere in the Kashevarof anticlinorium. A system of north to northwest-trending faults of Tertiary age cuts the complex and enclosing rocks. Ten to 20 feet of postglacial uplift is recorded by raised banks of lignitic mud containing marine shells.

The composition of the minerals comprising the principal phases in the complex have been determined throughout the complex by measurement of optical properties and comparison with published correlations of optical properties and chemical composition.

All the mineral components of the complex change systematically in composition from the core of the complex outward. Olivine ranges from $Fo_{90}Fa_{10}$ in dunite to $Fo_{51}Fa_{49}$ in granulitized country rock. Augite, hypersthene, hornblende, and biotite tend to become richer in iron with increasing distance from the core of the complex. Plagioclase changes from Ab_5An_{95} to an intermediate to sodic plagioclase in outer parts of the gabbro ring and in altered country rocks. The change in each isomorphous series is toward the less refractory end member with increasing distance from the core of the complex. A systematic variation in composition of mineral phases related to a systematic, non-stratiform arrangement of genetically related rock units is here termed cryptic zoning.

Twelve chemical analyses of rocks from the Blashke Island complex and 2 analyses of outlying dikes are given. The norms and modes are given and the analyses are plotted on variation diagrams and a von Wolff diagram. Magnesia is shown to decrease regularly from the core of the complex outward. Lime is at a maximum in the olivine augitite ring and decreases inward and outward. Iron is nearly stable in tenor through most of the course of variation. Alumina is virtually negligible in the peridotitic rocks and becomes a relatively stable major component in the feldspathic rocks. Alkalis are absent in the peridotites and subordinate in the feldspathic rocks but increase outward. Correlative variations are shown for minor components. A major break in chemical relationships exist between the feldspathic and the peridotitic rocks, mainly owing to the presence of alumina as a major component in the former, where it substitutes in part for silica, and its absence in the latter.

Hypotheses of origin of concentrically zoned ultrabasic complexes involving separate solid, semi-solid and magmatic intrusions, ring dike mechanisms, deformation of stratiform differentiated bodies, crystal settling and convection, and metasomatism are shown to be inconsistent with observed relationships. An hypothesis is advocated by the author, involving the intrusion of an ultrabasic magma of the composition of wehrlite plus some water and other volatiles at a temperature above 1,000°C. This magma need not be entirely liquid but may consist of solid forsteritic olivine crystals suspended in one or more fluid phases. Upon intrusion into cooler and more silicic and alkalic rocks a temperature and concentration gradient is set up between magma and surroundings. Transfer of chemical components is supposed to take place along this gradient. Reasons are advanced for supposing that, at the probable temperatures and pressures prevailing, a gas phase escapes the magma and permeates the surrounding rocks. Toward the close of crystallization the liquid phase may disappear from the nearly crystallized magma and only a supercritical gas phase remain permeating intergranular spaces in all the rocks. It is suggested that rates of diffusion are rapid in an aqueous gas above critical temperature and pressure for pure water, and that large scale transfer of chemical components takes place by diffusion in such a medium. It is also suggested that if the original magma is oversaturated with water and other volatiles there will be an outward migration of fluids toward regions of lower vapor pressure where the magma is losing heat and this movement of fluids will cause a bulk migration of dissolved solids. The effect of transfer of chemical components along the temperature and concentration gradient by the above methods, or perhaps by other processes unknown to the author, is to bring the magma-body to a quasi steady-state in which olivine is stable in the hot core of the mass and crystallizes outward with cooling, while augite becomes the stable phase at the cooler margins of the magma body, where the concentration of lime and silica is higher, and crystallizes inward, replacing early-formed olivine. Heat exchange, emanation of volatiles, and outward migration of lime and magnesia gabbroize the surrounding rocks and locally convert quantities of it into fluid gabbro magma that resolidifies to form the gabbro ring of the complex. The origin of minor rock facies and relationships are developed in detail based on the above explanation of the major relationships, and the origin of an ultrabasic magma is discussed. Beerbachite dike rocks are attributed to the decomposition and mobilization of inclusions of both sedimentary and volcanic country rock.

All of the olivine-bearing rocks have been partially serpentinized. Serpentinization is shown to have been a volume for volume replacement in two or more stages that took place entirely subsequent to the emplacement of the complex. The initially formed serpentine is shown to be iron-bearing and a study of analyses of serpentinized peridotites indicates that the combined iron is in the ferric state substituting in part for silicon as well as magnesium. Part of the ferrous iron originally present in olivine is released as magnetite. Equilibrium data on iron oxides and water suggest that the oxidation of iron during serpentinization is effected by oxygen from the dissociation of water. Field and petrographic evidence suggest but do not prove that the initial stages of serpentinization are not related to the weathered profile or to avenues of later hydrothermal or groundwater attack but are deuteric and that a later stage is related to weathering.

The regional distribution of ultrabasic intrusions in Alaska and western Canada is summarized. The intrusions are found to fall into groups related to several periods of diastrophism and plutonic invasion. Areally the ultrabasic masses are grouped near the roof zones of batholithic masses of dioritic to granitic composition, but the ultrabasic intrusions antedate the batholithic rocks.

Juxtaposition in areas and time indicates that the ultrabasic intrusions and the batholiths are common products of a petrogenetic cycle, but the ultrabasic rocks are emplaced ahead of and above the batholiths and there is no evidence that can be observed in the field, aside from mere juxtaposition, for differentiation from a common magma. The ultrabasic intrusions and the batholiths are probably derived from quite different sources during the diastrophic process. They are common products of a process, not a magma.

The petrology and structure of the Kane Peak complex on Kupreanof Island is briefly described. It is shown to be a funnel-shaped body with inward dipping contacts between rock units, but the sequence of rock units from the core outward is similar to the Blashke Island complex. Some observations of the Mount Burnett complex on Cleveland Peninsula are summarized, indicating that although the complex is similar to the Blashke Island complex in the sequence and relationships of rock units, it passed into an elongated dome or a tabular mass toward its western end where the dunite core is overlain by olivine augitite and gabbro. In the Kane Peak complex the olivine augitite and other outer zones dip beneath the dunite core. In parts of the Mount Burnett complex the outer zones overlie the dunite core. These relationships are best explained by a process of differentiation, such as that advanced for the Blashke Island complex, that is independent to a considerable degree of the attitude and structure of the complex and its contacts with enclosing rocks.

Geography

The Blashke Islands and the other areas with which this report mainly deals are located in southeastern Alaska (fig. 1, p. 8). The Blashke Islands are a small cluster of islets belonging to the Kashevarof group in Clarence Strait at the junction of Stikine Strait and Kashevarof Passage near the north end of Prince of Wales Island, lat. 56° 07'N. long. 132° 54'W. The Blashke Islands are 72 miles N.43°W. of Ketchikan and 31 miles S.41°W. of Wrangell. The other areas that will be described briefly are Kane Peak near Cape Strait on Frederick Sound, 13 miles N.28°W. of Petersburg, Lat. 56° 59'N. long. 133° 05'W., and Mount Burnett on Cleveland Peninsula, 36 miles N. 34°W. of Ketchikan, lat. 55° 47'N. long. 132° 08'W.

Southeastern Alaska is a deeply dissected mountainous area in a stage approximating late youth or early maturity, strongly modified by glaciation, with an intricately fjorded shore line. The relief at the Blashke Islands is negligible, amounting to only two or three hundred feet, while the other two areas have sharp relief of about 3,000 feet. The area is in the heart of the North Pacific rain forest and is densely wooded to timberline near 3,000 feet. Reference is made to Buddington and Chapin (1929, pp. 10-37) for detailed geographical information.

The areas are accessible by boat or sea-plane only. In the summer of 1946 the Blashke Islands were inhabited but since abandoned by a family of three engaged in fishing and occupying a cabin and boat-house in Blashke Harbor. The islands have been occupied sporadically by an occasional fisherman, trapper or mink farmer in the past. Both Blashke Harbor and Bivouac Bay are excellent small boat anchorages, but the approaches are intricate and tricky, though negotiable by boats up to sixty or seventy feet in length and at least ten feet in draft. Spud Bay and Trap Bay have been used at times for beaching and winter storage of floating salmon traps, and a few timbers have been cut from the northern shores of the islands. Otherwise the islands are in a complete state of nature.

A feature of considerable importance to the geologist as well as the boatman is the very great rise and fall of the tides, ranging from twelve to more than

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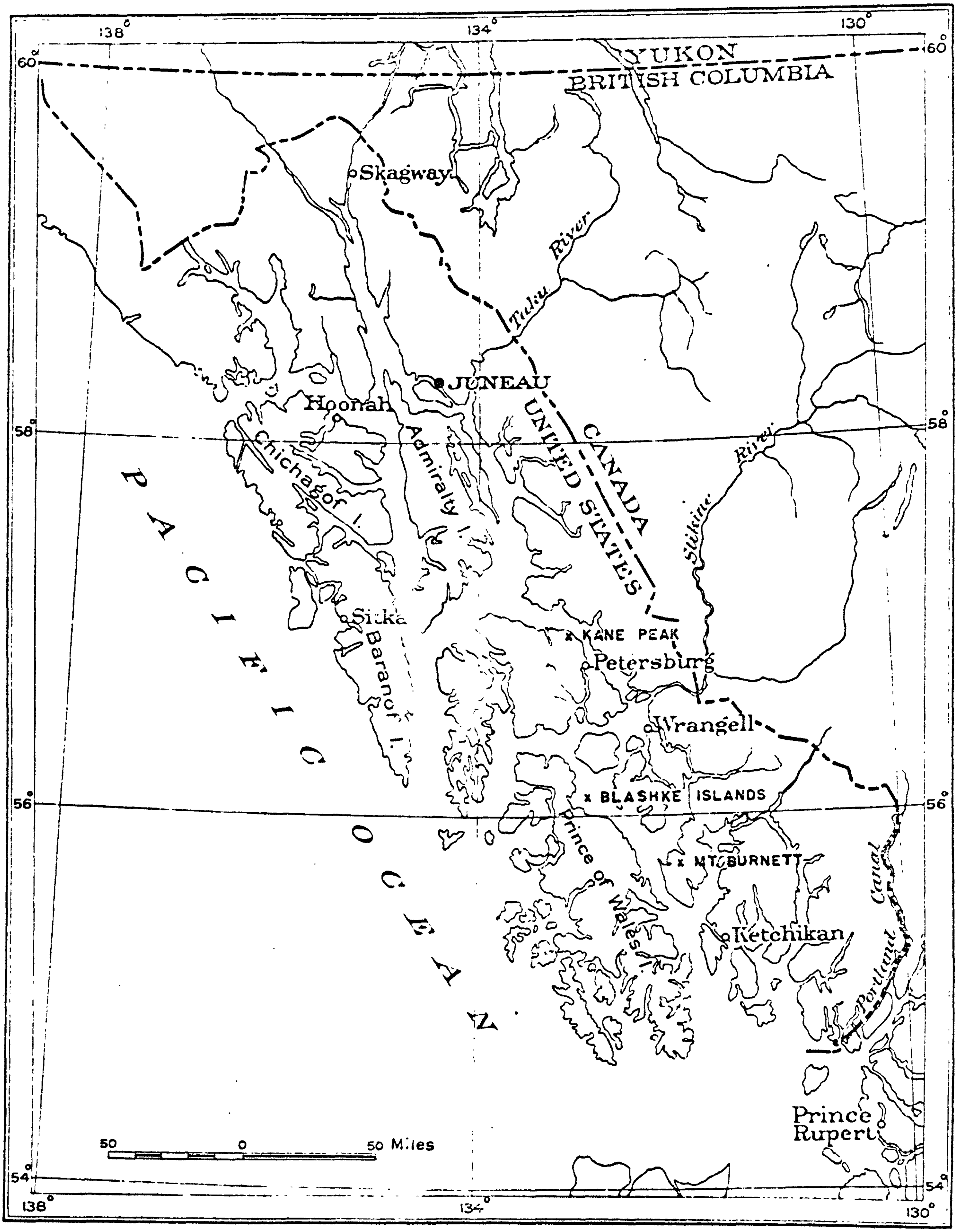

FIGURE 1.– INDEX MAP SHOWING LOCATION OF BLASHKE ISLANDS, KANE PEAK AND MT. BURNETT DIFFERENTIATED ULTRABASIC BODIES, SOUTHEASTERN ALASKA

enty feet between high and low tides, resulting in almost continuous exposures wave-washed rock between high and low tide level, but producing violent tidal rrents in the channels and inlets. Inland from the shore there is dense forest muskeg and exposures are very poor except for the dunite areas of the ultramafic mplex. The weathering of dunite produces little of the soil components required plant life and only a scanty scrub vegetation grows.

There is no culture or development of any kind in the Kane Peak area and no nable anchorage, even for a small boat, along the shore. Relief is from sea-vel to a little over 3,000 feet. The slopes up to above 2,000 feet are heavily rested and exposures are relatively poor in spite of their steepness. The core the ultramafic rock area is well exposed due to infertile soil, but contacts th enclosing rocks are visible in only a few places.

The Mount Burnett area extends from Union Bay to Vixen Inlet on the Cleveland ninsula. A salmon cannery is located on Union Bay and there is an occupied olling at Vixen Harbor. Away from the shore there are no trails or other developnts. Relief and exposure are comparable to the Kane Peak area. Plates 2, 3, d 4 show general views of these areas.

Previous Work

The Blashke Islands, Kane Peak, and Cleveland Peninsula were briefly examined d their salient geological character described by Buddington (Buddington and apin, 1929, pp. 190-194) in the course of his areal geologic mapping of south-stern Alaska. They were briefly examined by George C. Kennedy and the author the summer of 1943, but have not hitherto been studied in detail.

Field Work and Acknowledgments

The field work on which this report is based was begun in 1943 in connection th the war minerals investigations of the Geological Survey. At that time, under the leadership of George C. Kennedy, two weeks were spent on the Blashke Islands, a few days at Kane Peak, and several weeks at Mount Burnett. The results of this work have been published in Geological Survey Bulletin 947-D (Kennedy and Walton, 1946, pp. 75-83).

Field work on these areas was resumed by the present author in the summer of 1946. Work was started on June 23, 1946, at the Blashke Islands and continued until the middle of August during which time a plane table map on a scale of 1:6000 was made of the shore lines of the islands, along which practically all of the significant exposures lie, and the islands were mapped in detail geologically with particular attention to the eruptive rocks. Ten days were spent during August at Kane Peak. A rough topographic base map for this area was made by chaining, pace-compass, and barometer, and a geologic reconnaissance map made of the ultrabasic mass together with detailed observation of some of the features of the southern and western contacts. About a week was spent in September at Mount Burnett where some additional observations were made on the structure of the ultrabasic complex, particularly in the area between Mount Burnett and Union Bay. The party consisted of two, the author, and Mr. Ivan Tolstoy, who, though employed as a camp hand, ably discharged the duties of a geological assistant.

The writer wishes to acknowledge his indebtedness to his associates in the Geological Survey and particularly to George C. Kennedy, who originally inspired this investigation and whose companionship and generous participation in many discussions has been a continued source of stimulation. I am also much indebted to Professor S. J. Shand of Columbia University and to the geology departments of Columbia University and Yale University where much of this report was prepared while on W.A.E. status in the Geological Survey. Following Professor Shand's retirement, Professor Adolph Knopf of Yale graciously undertook to read this report and to counsel the author. His guidance is deeply appreciated and has contributed much to this paper. The only inhabitants of the Blashke Islands, Mr. Lee Byington, his wife Beulah, and his daughter Patricia, extended many courtesies and kindnesses and gave much information on navigating the difficult water around the islands.

Peridotite Complexes in Southeastern Alaska

There are at least 8 well-defined peridotite complexes in southeastern Alaska (nos. 11 to 18 incl., fig. 2, p. 12). These masses differ widely in size, though none are large, and also differ in petrology and structure. However, certain features are common to all of them, chiefly that they all are composed of, or contain within their cores, extremely basic rocks consisting largely of olivine or olivine and pyroxene. An exception is the body at the head of Kasaan Bay at the Salt Chuck locality (no. 18, fig. 2, p. 12). This body exposes only pyroxenite and mafic gabbro and is somewhat doubtfully included among the others.

Structurally there appear to be some significant differences that will be taken up in more detail in a later section. Briefly, the Blashke Islands complex, (fig. 2, area 15) appears to be a nearly cylindrical mass with roughly vertical walls, somewhat irregular in detail. The surrounding bedded rocks are crudely conformable to the contacts of the complex, but there is evidence for structural disturbance during the emplacement of the complex. On the other hand the peridotite mass at Red Bluff Bay (fig. 2, area 11) is described by Guild and Balsley (1942, p. 177) as having a concordant, spoon-shaped lower contact plunging in the direction of the regional fold axes. The term "phacolith" may fit this body (Harker, 1909, p. 78). In the same area are a number of sill-like serpentine bodies that conform closely to the regional foliation (Kennedy and Walton, 1946, pp. 72-73).

The complex at Kane Peak (fig. 2, area 14) is shown by map relationships and two observed contacts to be a funnel-shaped body with inward dipping contacts that are probably steep (45°-or more). The surrounding bedded rocks are probably more or less conformable. The mass at Mount Burnett (fig. 2, area 16) was described by Kennedy and Walton (1946, p. 81) as a composite stock, but a further reconnaissance of the area during the present investigation suggested the definite possibility that this is a tilted, tabular mass. The area requires further study. Little or no structural data is available on the other ultrabasic complexes in southeastern Alaska.

The internal structural elements of these several masses also display differences. The Blashke Island complex has a distinct, though not perfect, concentric arrangement with an inner core of dunite and a composite outer ring of peridotite, pyroxenite, and gabbro. The mass at Red Bluff Bay shows an irregular banding and inter-lensing of dunite and pyroxene-rich rocks described by Guild and Balsley (1942, p. 177) as flow layering. However, pyroxene-rich rock shows some tendency to be concentrated near the base and on the margins, that is, peripherally, and the banding is generally steep and oriented with the long axis of the mass. The internal relationships of the complex at Kane Peak are more irregular and varied than at the Blashke Islands or at Red Bluff Bay, but olivine-rich rocks are also concentrated in the core of the mass. As mentioned above, the possibility exists that the mass at Mount Burnett is a tilted, tabular mass with a core of dunite. According to Koschmann (1936, pp. 268-274), the Duke Island and Annette Island bodies are largely hornblendite, but contain within them masses of harzburgite and augitite.

The largest of these ultrabasic masses is probably the complex on Duke Island extending in a belt about 10 miles long across the island with an outcrop area of about 20 square miles. The mass on Cleveland Peninsula is about seven miles in greatest exposed length with an area of about 14 square miles. The Blashke Island complex is almost circular and about two miles in diameter with an area of about 3.5 square miles. The Kane Peak Complex is partly covered by the waters of Frederick Sound, but the major part of it is exposed with an area of about 2 square miles, and the mass at Red Bluff Bay is about the same size. The other bodies are smaller and less is known about them.

The region in which these ultrabasic bodies occur is one of complex mountain structure. Rocks of Ordovician or older to Cretaceous age have been tilted, [illegible], invaded by the Coast Range batholith and many lesser intrusions, and regionally metamorphosed in an extensive belt along the western margin of the batholith. As stated by Buddington (Buddington and Chapin, 1929, pp. 10-37) only the broader features of the region are known, but it is clear that though there have been earlier orogenic episodes, the Jurassic-Cretaceous orogeny with which the Coast Range batholith is correlated is the major period of deformation and deep-seated eruptive activity.

According to Buddington (Buddington and Chapin, 1929, pp.10-37) the ultrabasic complexes are emplaced within rocks ranging in age from Ordovician or older to Cretaceous. The ultrabasic bodies at Duke and Annette Islands and on Cleveland Peninsula (fig. 2, areas 17 and 16) are emplaced in rocks of the Wrangell-Revillagigedo metamorphic group of indefinite age. The Blashke Island complex is emplaced in rocks of Ordovician and Silurian age. The Red Bluff Bay body is in rocks regarded by Guild and Balsley(1942, p. 177) as Upper Triassic. The Kane Peak complex is in contact with rocks doubtfully correlated by Buddington with the Cretaceous but possibly Upper Jurassic. The peridotite masses on Tracy Arm and Ford's Terror (fig. 2, areas 13 and 12) are within the Coast Range batholith and described by Buddington (Buddington and Chapin, 1929, pp. 10-37) as being cut by granitic dikes, showing that they antedate at least part of the granitic intrusive activity.

An upper limit of geologic age can be established for the Mount Burnett complex on Cleveland Peninsula. The complex is older than a conglomerate containing plant remains and boulders of ultrabasic rock correlated with the Port Camden basal Eocene by Buddington (Buddington and Chapin, 1929, pp. 10-37). This conglomerate is exposed lying on an erosion surface of pyroxenite and hornblendite of the complex as well as slate and phyllite of the enclosing rocks. The complex is therefore pre-Eocene.

The Blashke Island complex is cut by a basalt dike correlated by the present author with the Tertiary basalts described by Buddington (Buddington and Chapin, 1929, pp. 271-273).

The youngest rocks known to be invaded by one of these complexes are the Upper Jurassic or Cretaceous slates and graywackes on Kupreanof Island invaded by the Kane Peak complex. Pre-Eocene age is indicated by the overlying Eocene conglomerate on Cleveland Peninsula. The ultrabasic rocks are therefore late Jurassic or Cretaceous in age, depending on the true age of the youngest sediments that they cut, and are correlated with the major orogenic episode of the region.

Buddington's (Buddington and Chapin, 1929, p. 242) conclusion based on all the evidence available to him is that the ultrabasic rocks of southeastern Alaska are older than the more siliceous-alkalic types of this petrogenic province. This evidence consists in part of observed field relationships in which the ultrabasic rocks are seen to be intruded by more siliceous-alkalic rocks, and in part on general petrogenetic considerations. All of the Canadian writers, to whom later reference will be made, are in agreement that the field relationships show the ultrabasic rocks of British Columbia and the Yukon Territory to be older than the more siliceous rocks belonging to the same period of intrusion. The only field relations observed in the course of the present investigation bearing on this problem are in the Kane Peak area where a dioritic body is in contact with the ultrabasic complex. Both rocks show mineralogic and textural alteration near the contact, and the evidence is somewhat ambiguous, but on the whole suggests that the ultrabasic rock was invaded by the dioritic rock. Somewhat more conclusive evidence is afforded by the presence of granodiorite and minette dikes in a fault zone that cuts the south side of the ultrabasic complex, because both the fault and the dikes are clearly later than the complex, and the dikes are presumably related to the diorite-granite sequence of intrusions. It seems to be in line with available field evidence and acceptable to the workers in this region to consider the ultrabasic rocks with which this report deals to belong to the Jurassic-Cretaceous period of intrusive activity, and to be the oldest plutonic rocks of the Jurassic-Cretaceous petrogenetic cycle.

The Blashke Island Complex

Introduction

The general geologic relationships exposed on the Blashke Islands are shown on the geologic map (plate 1). The complex consists of a nearly circular mass of peridotitic rocks surrounded by an irregular rim of gabbro. The overall diameter of the complex is from 10,000 to 12,000 feet with an area of about 3.5 square miles. The center of the peridotite mass is dunite, a rock composed primarily of olivine and serpentine derived from the alteration of olivine. The core is crudely circular with many irregularities in detail and from 6,000 feet to 9,000 feet in diameter. Surrounding this core of dunite is a rim of pyroxene-rich peridotite consisting principally of augite, but almost everywhere containing appreciable amounts of olivine. This rock is termed olivine augitite in this report. Near the contacts between dunite and olivine augitite the dunite commonly contains sparse to abundant interstitial augite and passes gradationally into wehrlite. Within the pyroxenitic rim there are bands and irregular streaks of rock in which olivine is as abundant as or in excess of pyroxene and the rock may also be classed as wehrlite. The pyroxenite rim has a maximum width of about 1,500 feet on the east side of the complex and is somewhat irregular and only a few hundred feet wide on the west side of the complex. Two short, thick, lenticular dikes of pyroxenite were found cutting thin bedded hornfels several hundred feet from the main mass of the complex.

The concentric structure of the ultrabasic complex is further expressed by a ring of gabbro outside the pyroxenitic ring. This gabbro ring is highly irregular in width, texture, internal structure and composition. Unlike the pyroxenite ring, which everywhere surrounds the dunite, it is absent in places, and the peridotitic rocks are in contact with the country rocks. The gabbro ring is widest in outcrop at the northeastern edge of the complex where practically continuous exposures of gabbro have a maximum width of about 1,400 feet. The gabbro ring is relatively wide and continuous along the eastern edge of the complex, and although part of the complex is beneath the sea along the southern margin, outcrops of gabbro in the southeasternmost large island and in a couple of reefs exposed at extreme low tide indicate that gabbro is present and may extend more or less continuously around the southern boundary of the ultrabasic rocks.

There is good evidence in the form of intense shear zones for strong faulting along the southwestern edge of the complex, and this faulting has probably cut out any gabbro that may have been present as well as a good part of the pyroxenitic ring of the complex, as far north as the small bay at the elbow of the channel into Bivouac Bay. However, the exposures of gabbro from the channel into Bivouac Bay northward have a different aspect than the broad, well-developed gabbro band along the eastern margin of the complex. It is impossible to say how much gabbro is concealed beneath the waters of Bivouac Bay, but such exposures as are present consist of irregular dike-like masses with many inclusions and brecciated masses of hornfelsed country rock irregularly veined by gabbro apophyses from a few feet to a fraction of an inch in width. At one point, the westernmost exposure of ultrabasic rock, a somewhat peculiar facies of the peridotite consisting of a feldspathic wehrlite, is in sharp contact with hornfelsed conglomerate with no intervening gabbro.

The gabbro is sporadically developed along the narrow channels around the northern rim of the complex, but here also it may be partly cut out by faulting. However at two points an olivine augitite containing bands approaching gabbro in composition by the admixture of coarse anorthite is in direct contact with hornfelsed country rock.

In addition to the gabbro immediately contiguous to the complex there are several outlying masses and thick dikes of gabbro, particularly near the entrance and at the northern end of Blashke Harbor and along the northern shore of the southeasternmost island. One mass of gabbro is found within the olivine augitite band near the southeastern rim of the complex. This mass of gabbro is in sharp contact with the olivine augitite on its south side, but the contact, where visible, on the north and east side of the mass is a low angle fault dipping 25° westward. In spite of the low angle of this fault it seems more likely that it is a normal fault bringing the gabbro down from the east rather than up from the west.

In contrast with the olivine augitite ring surrounding the dunite core of the complex, which is virtually complete in that nowhere can dunite be found in contact with anything but olivine augitite, the gabbro ring is irregular, and in at least three places it is absent with a somewhat aberrant facies of the peridotite in contact with altered country rocks. However, the asymmetry of the gabbro ring is matched by a certain degree of asymmetry in the olivine augitite ring of the complex which is wider and more uniform along the eastern side of the complex, while the western side is narrow and contains streaks and bands of wehrlite. Structural data indicate that the contacts between the major rock units of the complex are irregular both in plan and in vertical extension but tend to dip steeply outward with many irregularities and reversals, although the downward extension of the complex at the level at which it is exposed appears to be effectively steep, just as the outcrop of the complex and its major elements is effectively circular despite many irregularities. If the strong north to northwest trending faults that cut the complex have had much vertical displacement along them, the eastern side of the complex may be structurally some distance above or below the western side, and the differences in petrologic relationships between the eastern and western sides may be because different levels are exposed.

The complex of basic and ultrabasic rocks is emplaced within a varied sequence of stratified rocks that have undergone low grade regional metamorphism to chloritic and amphibolitic greenstones. Within a few hundred feet of the ultrabasic mass these rocks are strongly hornfelsed to biotite-hypersthene-plagioclase-augite granulites some of which contain an iron-rich olivine.

No stratigraphic work has been done in this area in sufficient detail to permit satisfactory correlations to be made, but three distinct lithologic types of bedded rocks were recognized and mapped by the author. The first consists of strongly indurated, fine-grained rocks ranging from laminated and thin-bedded to massive. These rocks are low grade metamorphic equivalents of mudstones, shales, cherts, and volcanics. They are characterized by abundant chlorite but lack foliation or strong slaty cleavage. The second consists of similarly metamorphosed coars conglomerate of varied lithology including much volcanic material with interbedded laminated fine-grained rocks and a few bands of coarse white marble. The third consists of practically unmetamorphosed, thin-bedded to shaly, dove-gray to white limestone outcropping in a few areas at the north end of the islands and apparently overlying the other rocks unconformably. No recognizable fossils were found in these rocks and they have been mapped on the basis of lithology alone, mainly for the purpose of revealing the structural displacements related to the complex.

Buddington (Buddington and Chapin, 1929, pp. 10-37, pl. 1) has indicated on the Geologic Map of a Portion of Southeastern Alaska, which is on a scale of 1:500,000 and thus highly generalized, that the thin-bedded to massive hornfelses outcropping around the northwestern rim of the Blashke Island complex are correlated by him with lower and middle Ordovician rocks that outcrop about 4 miles to the west on Thorne Island. These rocks are said to consist predominantly of indurated graywacke containing graptolites. The predominantly conglomeratic rocks are mapped by Buddington (Buddington and Chapin, 1929, pp. 74-75) as Silurian, belonging to the next to the lowest Silurian unit recognized by him, and described as consisting of andesitic volcanics and conglomerate, some associated graywacke, black slate, limestone, and tuff (Buddington and Chapin, 1929, pp. 82-63). The thin-bedded and shaly limestones at the northern end of the islands evidently belong to the Silurian limestones of the next overlying Silurian formation which Buddington has mapped on several of the small islands a mile or more to the north (Buddington and Chapin, 1929, pp. 83-84).

So far as the present work is concerned the rocks of sedimentary origin were mapped on the basis of lithology, there being no basis for establishing a time-stratigraphic division within the area itself, but the mainly fine-grained, thin-bedded to massive rocks that are in contact with the ultrabasic mass except on the easternmost islands are probably correlated with the Ordovician, and the mainly conglomeratic rocks probably belong to the Silurian.

Within the surrounding rocks of volcanic and sedimentary origin there are innumerable dikes, ranging from gabbro and basalt to diorite and andesite, that may possibly be related to the ultrabasic intrusion.

The petrology of the Blashke Island complex will be described in detail in the following pages. The peridotites, gabbros, gabbroic hornfelses, and closely related rocks will be taken up first beginning with a brief description of the principal rock types and their characteristic relationships, followed by a detailed description of the principal mineral phases and their variations in composition and petrologic relationships throughout the complex, and concluded by a detailed discussion of the petrology with micrometric data on the modes and important variants of the principal rock types. Finally the country rocks including dikes not related to the ultrabasic complex will be described.

The Peridotitic Rocks

The peridotites of the Blashke Island complex, considered from a broad point of view, consist of two principal rock types: a core of rock composed primarily of olivine in which augite enters locally as a marginal phase, and a rim of augite rock containing varying amounts of olivine, the augite being near diopside in composition. From a purely statistical standpoint there is no hard and fast boundary between rocks consisting almost entirely of olivine and rock in which augite is the major constituent. All gradations may be found from dunite entirely free of pyroxene to pyroxenite that is virtually free of olivine. In the field, however, the contacts between these major rock types are not commonly smoothly gradational. Augite appears in the olivine rock as a subordinate, interstitial phase near the contacts with the pyroxenitic rocks. It tends to increase in abundance as the contacts are approached, but the contacts with pyroxenitic rocks are either sharp or abruptly gradational within a few feet or inches in most places.

Gradational relationship between rock types is the dilemma of nomenclature and classification. In the case of the peridotites the term dunite is well established for rocks consisting essentially of olivine and the terms, pyroxenite, augitite, diallagite, etc., and used for rocks consisting primarily of a pyroxene. Common usage permits the term dunite to encompass rocks containing a small percentage of accessories, of which chromite, ilmenite, magnetite, picotite, spinel, and pyroxene are the most common. This implies that small amounts of these minerals do not have genetic significance. In the Blashke Islands it is probably true that the ore minerals are at least of minor genetic significance, but it will be shown that the appearance of augite in minor amounts is indicative of a rise in the fayalite content of the olivine above a minimum value. Thus, strictly speaking, any amount of pyroxene, however small, is significant from the genetic and classificatory standpoint. On the other hand, in the field, it was noted that rocks containing less than ten or twelve percent pyroxene were generally closely associated with dunite as a marginal facies and in most cases passed gradationally into dunite but were commonly in sharp contact with rocks with a distinctly higher pyroxene content. On the basis of this field tendency the practice followed in this report will be to use the name dunite to apply only to olivine rocks virtually free of pyroxene, but usually containing accessory ores. Rocks containing less than 12.5 percent augite and other accessories will be termed augite-dunite.

The name wehrlite (Rosenbusch, 1887, p. 267) will be applied in this report to rocks composed primarily of olivine and augite and their alteration products with minor accessories, mainly chromite and magnetite, in which olivine is in excess of augite. Here again field relations afford some degree of justification for this arbitrary and artificial division by rock names. In the field only a few instances were found where rocks containing more pyroxene than olivine seemed to be related by gradation more closely to dunite than pyroxenite.

A number of names have been applied to rocks in which a clinopyroxene is the principal mineral, but none seem to be strictly applicable to the augite-rich rock of the Blashke Islands. These rocks consist of augite, olivine, and accessory ores. Hornblende is present in many specimens, but typically as an alteration product of pyroxene and not as a primary mineral. Olivine may be present only by proxy in the form of serpentine pseudomorphs. However, the practice adopted in this report has been to consider hornblende and serpentine as representing the primary minerals from which they were derived for the purpose of classifying the rock.

The name wehrlite is frequently employed for any clinopyroxene-olivine rock whether the pyroxene exceeds the olivine or not. However, in the Blashke Island complex there is definite need for a name both for rocks in which olivine is in excess of pyroxene and vice versa. The name montrealite was given by Adams (1913, pp. 28-29) to a rock consisting of clinopyroxene, hornblende, and olivine in order of abundance with or without minor amounts of plagioclase, orthoclase, and nepheline. Bancroft and Howard (1923, p. 19) described this rock as wehrlite but reported essential quantities of hornblende. Johannsen (1938, pp. 430-432) has advocated using montrealite for rocks containing clinopyroxene and hornblende with less olivine, but has suggested no name for a similar rock in which no primary hornblende is present. Furthermore the original montrealite is a facies of an essexite body low in salic constituents, but which may contain minor amounts of both nepheline and orthoclase in addition to plagioclase. The only light-colored constituent of the Duke Island rock is a very small amount of sparsely and sporadically disseminated calcic plagioclase up to An96 in composition. This contrast in minor constituents reflects a fundamental genetic difference that should not be overlooked in classification.

The names pyroxenite, augitite, etc. are sometimes employed loosely to include rocks with quite substantial amounts of olivine on the one hand or of salic constituents, mica and hornblende on the other. As Shand (1947, pp. 118-121) has pointed out this practice overlooks the significance of saturation or undersaturation with silica and results in the lumping together of rocks with diverse origins. In order to avoid ambiguity and at the same time avoid coining another rock name, the name olivine augitite will be employed to designate all rocks in which augite is the principal constituent, accompanied by olvine and accessories. Where the rock contains more than 25 percent olivine, as it does in only a few instances, the name will be further modified to wehrlitic olivine augitite.

In addition to the major rock types of the peridotitic part of the complex, which belong to the dunite-wehrlite-augitite sequence, there are a number of minor rock types that are closely associated with those major units, appearing in them as dikes, veins, or irregular masses. Most of these rocks are characterized by the presence of a calcic plagioclase, primary hornblende, or both, and by aplitic or pegmatitic textures.

Dunite, Augite dunite, and Wehrlite

The dunite of the Blashke Islands is characteristically deep bluish-green on freshly broken surfaces, but the color ranges from flat, sooty black to dirty yellowish-green. Megascopically the texture appears fine-grained, almost aphanitic. Actually the rock is coarse grained and the aphanitic appearance is due to serpentinization. In addition to olivine and serpentine, well-formed, small, black octahedrons of chromite can be identified in the hand specimens. The rock may show a distinct platy structure due to the sub-parallel alignment of closely spaced serpentine veinlets.

Augite dunite and wehrlite resemble dunite in texture but the color on fresh surfaces is typically sooty black rather than bluish-green. Cleavage faces and bottle-green grains of augite can be identified. Both olivine and serpentine characteristically weather a smooth, yellowish to reddish buff resembling chamois or suede leather. This so-called chamois surface is a fairly reliable indication in the field of the presence and abundance of olivine and serpentine. The clear green pyroxene is virtually unchanged in color by weathering and stands out clearly against the buff, chamois surface of olivine and serpentine, usually in moderate relief. On the other hand, on fresh surfaces it may be difficult to detect small percentages of olivine in pyroxenite or of pyroxene in dunite. Weathering in effect provides a fairly sensitive and reliable qualitative chemical test of the presence of these minerals in association with each other.

In thin section the rock is seen to consist of a granular aggregate of more or less equant, anhedral olivine grains from a few millimeters to more than a centimeter in cross section, averaging 20 to 40 grains per square centimeter. Where olivine is unaccompanied by pyroxene the grains form a closely packed mosaic with few grains showing any trace of crystal form, but with simple, unsutured boundaries between grains. The texture is simple allotriomorphic granular. Where pyroxene is present in small amounts it is interstitial, with olivine displaying rounded, somewhat imperfect crystal forms against anhedral augite. Adjacent interstitial areas of pyroxene may have the same crystallographic orientation indicating an incipient poikilitic texture which is realized where pyroxene is abundant. Poikilitic pyroxene enclosing olivine in random orientation is shown in photomicrographs A and B, plate 16. Clinopyroxene is clearly a late interstitial phase in these rocks. Although the grain size of the olivine is typically coarse, each grain is without exception transected by a network of curving fractures filled with serpentine, which divide each grain of olivine into numerous angular to subangular shards, few as much as 2mm in cross section.

Serpentine is present in all specimens of dunite, augite dunite, and wehrlite from the Blashke Islands in the form of fracture fillings in crackled olivine and along grain boundaries. It is also present in many specimens as complete pseudomorphs after olivine, and to a lesser extent as thin fracture-fillings in pyroxene. In most specimens of dunite as well as augite dunite and wehrlite the spacing of serpentinized fractures is so close that the actual volume of serpentine in the rock is commonly greater than the volume of unaltered olivine. In augite dunite and wehrlite the olivine tends to be somewhat less serpentinized than in the pure dunite.

Modes for dunite, augite dunite, and wehrlite together with other data are given in sections 1, 2, and 4 of table 1. Modes for an uncommon type of wehrlite found at the outer contact of the peridotitic part of the complex in sharp contact with hornfelsed conglomerate are given in section 9. The average values for the modes are recapitulated in columns A, B, D, and J of table 2 and chemical analyses are given. All modes were determined on thin-sections by means of either the Leitz integrating stage or the point counting method described by Chayes (1949, pp. 1-11).

Augitite, Olivine augitite, and Wehrlitic Olivine augitite

Augitite free of olivine is so rare on the Blashke Islands as to be a curiosity. Only one thin section out of more than thirty sections of this group of rocks contained no olivine. This rock consists of nodular masses of pure augite up to several inches in cross section in a mesostasis of normal olivine augitite; however another section from the same specimen included part of the mesostasis containing olivine. The typical olivine augitite is coarse to very coarse grained and dark green in color with irregular sooty black areas representing more or less serpentinized olivine. The weathered surface also is dark green with a rough, pitted texture due to the weathering out of olivine and serpentine and to the coarse granular character of the rock. Locally there may be a little

Table 1. Mineralogic data and Modes for Blashke Island rocks.

Item No.	Specimen No	Olivine			Augite					Mode								Remarks
		Ny	Fo	Fa	Ny	2V	Ca	Mg	Fe	Olivine	Serpentine	Aug.	[illegible]	Chromite	[illegible]	Chlorite	Talc	
																		Section 1. Dunite
1	322	1.672	90	10						31.2	68.3	-	-	0.5	-	t.	-	
2	C	1.672	90	10														
3	396	1.672	90	10														
4	319	1.672	90	10						29.9	69.7	v.s.t	-	0.4	-	-	-	
5	324	1.673	89.5	10.5						36.7	60.6	v.s.t.	-	2.7	-	-	-	
6	315	1.673	89.5	10.5						27.0	72.1	-	-	0.9	-	t.	-	
7	316	1.673	89.5	10.5						16.6	83.2	-	-	0.2	-	t.	-	
8	267	1.673	89.5	10.5						34.2	64.6	-	-	1.2	-	-	-	
9	268	1.673	89.5	10.5						49.2	50.3	v.s.t.	-	0.5	-	-	-	
10	303	1.674	89	11						19.4	78.2	v.s.t.	-	2.4	-	t.	-	
11	392	1.674	89	11						39.4	59.3	v.s.t	-	1.3	-	-	-	
12	345	1.675	88.5	11.5						30.9	65.5	-	-	3.6	-	-	-	
13	320									33.4	66.6	-	-	-	-	-	-	
14	318									28.6	70.8	-	-	0.6	-	-	-	
15	317									43.3	54.4	v.s.t	-	2.3	-	-	-	
16		1.673	89.5	10.5						32.2	66.5	v.s.t.	-	1.3	-	t.	-	
																		Section 2. Augite Dunite
17	305	1.672	90	10						35.0	63.6	1.2		0.2	-	-	-	
18	188	1.675	88.5	11.5						31.4	66.4	t		-	1.7	0.5	t	Cut by secondary veins of chlorite and calcite.
19	269	1.676	88	12						33.8	65.6	0.5		0.1	-	-	-	
20	161	1.676	88	12	1.683		44	49	7	21.0	67.4	7.3	t	2.0	2.3	-	t	
21	176	1.677	87.5	12.5	1.682	55.5	46.0	46.5	7.5	37.5	55.4	2.4		1.3	1.4	t	-	
22	177	1.677	87.5	12.5	1.684	54	44	48	8	44.1	48.8	6.3		0.4	0.4	-	-	
23	181	1.678	87	13		55.5				49.2	48.5	t		0.3	2.0	t	-	
24	182	1.678	87	13						52.6	46.5	t		0.6	0.3	t	t	
25	440	1.678	87	13						46.8	46.7	5.0		1.0	0.5	-	-	
26	179	1.679	86.5	13.5	1.680	56	47	46.5	6.5	29.5	64.3	4.6		-	1.1	0.5	-	(p.56)
27	C136	1.679	86.5	13.5	1.681				6	36.7	56.7	3.4		-	2.6	t	1.2	
28	183	1.680	86	14	1.684	55	45	47	8	46.1	42.6	10.5		0.7	t	-	-	
29		1.677	87.5		1.682	55	48	45	7	38.8	56.0	3.4	u.s.t.	0.7	1.0	0.1	0.1	

(In table 1 the units for the values given are:

Fo and Fa	molecular percent
2V	degrees
Ca, Mg, and Fe	atomic percent
Mode	volume percent
Ab and An	molecular percent
En and Fs	" "

Ny : intermediate refractive index
t : trace (less than 0.05% recorded in thin section analysis)
u.s.t. : very slight trace (mineral detected but none recorded in thin section analysis))

Table 1. Continued (2)

Item No	Specimen No	Olivine			Augite					Mode								Remarks
		Ny	Fo	Fa	Ny	2V	Ca	Mg	Fe	Olivine	[illegible]	Augite	[illegible]	[illegible]	[illegible]	[illegible]	*	
																		Section 3. Augite dunite dikes
30	252A	1.675	88.5	11.5						32.5	58.5	7.9	-	-	1.1	-	-	Dike in olivine augitite
31	111	1.677	87.5	12.5	1.684	54.5	44	48.5	7.5	33.3	59.6	6.0	-	1.1	-	-	-	Tabular mass in olivine augitite
32	427	1.678	87	13	1.683				7									Dike in olivine augitite
33	210	1.680	86	14	1.686	53	44	46	10	56.8	32.5	10.0	0.5	-	0.2	-	-	" " " "
34	133A	1.680	86	14	1.688	53.5	44.5	42.5	13	45.8	46.2	5.9	-	-	2.1	-	-	(pl.5) " " " "
35	Av.	1.678	87	13	1.685	54	44	47	9	42.1	49.2	7.5	0.1	0.3	0.8	-	-	
																		Section 4. Wehrlite
36.	178	1.676	88	12	1.685	56	47	43	10	33.9	52.9	11.9	-	-	1.3	-	-	All specimens are from border facies
37	5731	1.677	87.5	12.5	1.684	55	45	47	8	23.5	35.3	37.5	-	-	3.7	-	-	of dunite except item 45, specimen 133B
38	201	1.678	87	13	1.685	54.5	44.5	46.5	9	20.8	51.3	27.6	-	-	0.3	t	-	
39	275	1.678	87	13	1.684	55	45	47	8	10.6	65.8	23.2	-	-	0.3	t	-	
40	190	1.678	87	13	1.688				12.5	28.8	48.1	22.9	-	-	0.2	-	-	
41	340	1.679	86.5	13.5	1.686	54	44.5	45.5	10	33.7	48.6	15.8	-	-	1.3	0.6	-	
42	292	1.690	86	14	1.686	55	45.5	44	10.5	39.3	38.1	21.8	-	0.2	0.6	-	-	
43	247	1.681	85.5	14.5	1.684	54.5	44	48.5	7.5	34.4	51.3	11.5	-	-	0.7	-	2.1	*(pp.74, 115) Plagioclase, Ab6An94, (partly altered to leucoxene)
44	0134	1.684	84	16	1.685	54	44	47	9									
45	133B	1.686	83	17	1.686	54.5	45	44.5	10.5									(pp.24,70) Olivine-rich facies of olivine augitite.
46	175									19.3	60.5	15.3	-	-	4.9	-	-	
47	341									32.2	52.0	14.9	-	-	0.9	-	-	
48	Av.	1.680	86	14	1.685	55	45.5	45	9.5	27.7	50.4	20.2	-	t	1.4	0.1	0.2	
																		Section 5. Wehrlite dikes
49	296	1.676	88	12	1.684	55	45	47	8	16.3	44.1	36.8	2.0	t	0.8	t	-	Dike in olivine augitite
50	176	1.677	87.5	12.5	1.696				10.5									" " " "
51	193	1.677	87.5	12.5	1.687				11.5	17.8	51.9	27.9	0.3	-	2.1	-	-	" " " "
52	132	1.678	87	13	1.687				11.5	21.2	46.7	29.2	0.3	-	2.6	-	-	" " " "
53	134	1.678	87	13	1.694	55	45	47	8	28.6	34.2	34.8	-	-	2.4	-	t	*Talc " " " "
54	147	1.678	87	13	1.686	55.5	47	42.5	10.5	5.9	68.2	10.1	0.1	-	14.7	-	-	" " " "
55	151	1.682	85	15	1.686				10.5	12.4	35.7	49.3	0.2	-	2.4	-	-	" " " "
56	290	1.682	85	15	1.685				9									" " " "
57	344	1.684	84	16	1.686	55.5	47	42.5	10.5	42.3	35.0	20.9	2.1	-	1.7	-	-	" " dunite
58	0132	1.686	83	17	1.685	55	45.5	45	9.5									" " olivine augitite
59	Av.	1.680	86	14	1.686	55	45.5	44	10.5	20.6	45.1	29.8	0.7	v.st.	3.8	v.st.	v.st.	" " " "

Table 1. Continued (3)

Item	Specimen	Olivine			Augite					Plagioclase		Mode							Remarks
No	No	Ny	Fo	Fa	Ny	2V	Ca	Mg	Fe	Ab	An	Olivine	Serpentine	Augite	Hornblende	Plagioclase	Opaque	*	
																			Section 6. Olivine augitite, containing more than 12.5% olivine + serpentine
60	339	1.678	87	13	[illegible]				11			8.8	3.5	87.3	0.2	-	0.2	-	
61	252	1.680	86	14	1.686	54	44.5	45.5	11			7.5	13.2	78.2	0.4	-	0.7	-	
62	262	1.680	86	14	1.687	55	45.5	43	11.5			8.2	12.0	74.9	4.0	-	0.9	-	Inclusion in wehrlite, item 38, specimen 201
63	367	1.682	85	15	1.686	55.5	47	42.5	10.5			8.4	6.9	72.4	11.4	-	0.7	0.2	* Bastite
64	135	1.682	85	15	1.686	55	45.5	44	10.5			12.0	10.6	77.4	-	-	-	-	
65	276	1.684	84	16	1.686				10.5			11.6	10.7	76.4	0.7	-	0.6	-	
66	329	1.684	84	16	1.685	55	45.5	45	9.5			11.6	6.8	75.7	5.4	-	0.5	-	
67	137	1.684	84	16	1.686				10.5			9.1	8.8	71.7	9.5	-	0.9	-	
68	184				1.685				9							-			
69	462				1.688				12.5							-			
70	98					55						10.1	5.9	60.0	21.6	-	2.4	-	
71	Av.	1.682	85	15	1.686	55	45.5	44	11.5			9.7	8.7	74.9	5.9	-	0.8	t	
																			Section 7. Olivine-rich augitite dikes cutting normal olivine augitite
72	96	1.685	83.5	16.5	1.684				8			10.9	7.2	79.4	2.0	-	0.5	-	
73	186	1.685	83.5	16.5	1.687	53.5	44	45	11			11.3	21.4	67.3	-	-	-	-	
74	[illegible]	1.687	82.5	17.5	1.691	55	45.5	39.5	15			29.5	16.5	52.4	0.7	-	0.9	-	
75	Av.	1.656	83	17	1.687		44.5	44.5	11			17.2	15.0	66.4	0.9	-	0.5	-	
																			Section 8, Olivine augitite, containing less than 12.5% olivine + serpentine.
76	137	1.688	82	18	1.688				12.5										
77	192	1.688	82	18	1.688	55.5	46.5	41	12.5			4.7	7.0	87.9	0.1	-	0.3	-	
78	294	1.691	81	19	1.686	54.5	45	44.5	10.5			5.6	6.8	87.1	0.5	-	-	-	
79	141	1.693	80	20	1.688				12.5			7.3	2.7	83.6	6.4	-	-	-	
80	261	1.693	80	20	1.685	55.5	46	44	10			7.9	2.7	70.5	18.2	-	0.7	-	(pp 35, 166)
81	215	1.698	77.5	22.5	1.688	55.	45.5	41.5	13	<10	>90	3.5	0.8	85.4	4.1	5.5	0.7	-	(pp. 74, 115) Plagioclase altered to leucoxene.
82	235	1.703	75	25	1.694														
83	216	1.705	74	26	1.692	55	45.5	39	15.5	<10	>90	7.2	1.1	76.5	10.9	3.9	0.4	t	* (pp 74, 115) Talc
84	271				1.686	55	45.5	44	10.5			0.9	11.0	87.9	0.2	-	-	-	
85	211				1.688				12.5										
86	Av.	1.694	79.5	20.5	1.688	55	45.5	41.5	13	<10	>90	5.3	4.6	82.7	5.8	1.3	0.3	v.s.t.	
																			Section 9 Wehrlite, near contacts with country rock
87	365	1.679	86.5	13.5	1.687				11.5		(1)	4.5	43.0	50.3	0.8	t	0.8	t	* Talc and enstatite (1) (1) Plagioclase near anorthite
88	362	1.685	83.5	16.5	1.688	54	44.5	43	12.5		(2)	22.8	39.6	12.4	4.5	12.6 (3)	8.1	-	(2) Plagioclase near anorthite (pp. 70, 74) (3) Largely altered to leucoxene and unidentified isotropic substance (p. 70)
89	361	1.688	82	18	1.684	55	45	47	8			24.1	20.3	45.8	7.6	-	2.2	-	
90		1.684	84	16	1.686	54.5	44.5	45	10.5			17.2	34.3	36.2	4.3	4.2	3.7	v.s.t.	

Table I. Continued (4)

Ser. No.	Speci-men No.	Olivine Ny	Olivine Fo	Olivine Fa	Augite Ny	Augite 2V	Augite Ca	Augite Mg	Augite Fe	Plagioclase Ab	Plagioclase An	Mode Olivine	Mode Serpentine	Mode Augite	Mode Hornblende	Mode Plagioclase	Mode Opaque	Mode *	Remarks
91	97	1.692	81.5	18.5	1.684	55	45	47	8			23.5	6.3	63.3	5.3	-	1.6	-	Section 10. Olivine-rich augitite at contacts with country rocks.
92	122	1.695	79	21	1.692	54	44.5	37.5	18	<10	>90	11.1	3.0	81.0	4.2	t.	0.7	-	(p.78)
93	364	1.699	77	23	1.690	55	45.5	40	14.5	<10	>90	17.0	0.6	80.2	1.1	t.	1.1	-	(p.78)
94	Av.	1.695	79	21	1.689	55	45.5	41.5	13	<10	>90	17.2	3.3	74.8	3.5	t.	1.1	-	
95	410	1.679	86.5	13.5	1.684	55	45	47	8			20.0	41.2	12.9	-	-	25.9	-	(p.82) Section 11. Miscellaneous peridotite Koswite
96	345				1.693	54.5	45	38	17			-	19.4	80.6	-	-	-	t	(p.26) * Carbonate. Augitite dike in dunite
97	373				1.682				6.5										" " " "
98	167	1.690	81.5	18.5	1.687				11.5	6	94								(p.115) Feldspathic wehrlite dike in augite dunite.
99	325	1.691	81	19	1.688				12.5	7	93								(pl. 8)(p.74) Section 12. Gabbroic pegmatite Small, irregular mass in olivine augitite
100	244	1.698	77.5	22.5	1.687				11.5	4	96								(p.74,115) " " " " " "
101	233	1.703	75	25	1.693				17	7	93								(pp.71,74) Dike in olivine augitite
102	Av	1.697	78	22	1.689				14	6	94								
												Olivine	Augite	Hornblende	Plagioclase	Opaque	Alteration prod.	*	
103	390				1.679	56.5	48	46.5	5.5			-	63.4	-	-	-	2.8(1)	33.8	Section 13. Augite-garnet dike rock * (pp.29,56-7,72,131,163-5) Andradite garnet (1) Chlorite
104	333	1.697	78	22	1.690				14.5	6	94	34.6	29.0	10.4	25.2	0.8	-	-	(p.115) Section 14. Olivine beerbachite dikes
105	334	1.699	77	23	1.690	51.5	42.5	42	15.5	6	94	26.8	35.6	21.9	11.8	1.5	2.4(1)	-	(p.115) (1) Includes alteration products of plagioclase
106	367	1.700	76.5	23.5	1.693	53	44	39	17	9	91	14.2	34.3	22.4	26.0	3.1	-	-	(p.115)
107	137				1.695	53.5	44	37	19			9.6	35.5	20.4	28.3(2)	4.7	1.5(3)	-	(2) Most of plagioclase altered to [illegible] and an unidentified isotropic mineral, N≈1.66. (3) serpentine after olivine
108	Av.	1.699	77	23	1.692	53				7	93	21.3	33.6	18.8	22.8	2.5	1.0	-	
109	283				1.693				17	9	91	-	13.7	35.2	43.1	7.2	-	-	Section 15. Beerbachite free of olivine
110	205				1.697				20	12	88								(p.69)
111	141				1.688				12.5	14	86	-	20.5	55.1	22.7	1.2	-	0.5	* Hypersthene
112	99									16	84	-	0.7	82.4	15.0	0.9	0.6	04	(pp.23,137) * Hypersthene
113	214				1.691				15.5	16	84								
114	207				1.692	54	45	39	16	25	75								
115	Av.				1.692	54	45	39	16	15	85	-	11.6	52.6	27.2	3.1	0.2	0.3	
116	278				1.688	53.5	44.5	42	13.5										Section 16. Miscellaneous Outlying dike in country rock
117	261									75	25	-	2.2	-	72.0	0.3(1)	0.1	25.4	(pp.78,131,166) * Quartz (1) Apatite and sphene. Dike in augitite

Table 1. (Continued) (5.)

Item No	Specimen No.	Olivine			Augite					Plagioclase		Mode											*Mineral in starred column	Remarks (Alteration products where possible, [illegible])
		Ny	Fo	Fa	Ny	2V	Ca	Mg	Fe	Ab	An	Olivine	Augite	Ortho-pyroxene	Hornblende	Biotite	Plagioclase	Orthoclase	Quartz	[illegible]	Ore	*		
118	142	1.702	75.5	24.5	1.691	52	43	40.5	16.5	5	95	1.6	31.5	0.2	5.5	-	59.4	-	-	-	1.8	-		Section 17, Olivine gabbro, near [illegible] (pp. 35, 113, 115)
119	219	1.705	74	26	1.690	53	44	41	15	7	93	13.0	41.6	0.1	7.7	-	35.6	-	-	-	2.0	-		(pp. 34, 113, 115)
120	220					54				20	80	0.3	43.1	0.1	32.1	-	20.5	-	-	-	3.9	-		(pp. 113, 115)
121	Av.	1.703	75	25	1.690	53	44	41	15	11	89	5.0	38.7	0.1	15.1	-	38.5	-	-	-	2.6	-		
122	308				1.690	56	47	39	14	7/45	93/55	0.2	39.8	-	46.5	0.3	12.8	-	-	-	0.3	0.1	Prehnite	Section 18, Olivine gabbro, near granulite contacts
123	347	1.713	70.5	29.5	1.691	52	43	40.5	16.5	7	93	0.6	7.1	t.	33.3	-	53.5	-	-	-	5.5	-		
124	309				1.690	53	44	41	15	16	84	0.6	53.5	0.5	29.2	-	14.2	-	-	-	1.7	0.3	Prehnite	
125	Av.	1.713	70.5	29.5	1.690	54	44.5	40.5	15	10/45	90/55	0.5	33.5	0.2	36.3	0.1	26.8	-	-	-	2.5	0.1		
126	115				1.691	56	47	38.5	14.5	8/55	72/45	-	10.6	-	27.6	-	57.3	-	-	0.1	4.3	-		Section 19, Gabbro
127	120				1.691	54	44.5	40	15.5	16	84	-	13.5	-	33.7	-	47.0	-	-	t.	5.8	-		
128	15				1.691	56	47	38.5	14.5	17	83	-	4.4	-	18.1	0.2	68.4	-	-	0.4	5.5	3.0	Alteration products	
129	95				1.690	54	44.5	40.5	15	21	79	-	3.0	t.	39.2	-	54.6	-	-	-	1.3	2.5	Magnetite and antigorite pseudomorphs after olivine	
130	94					54				33	67													
131	104									(1)/75	(1)/25													(1) Minimum An value only. Contains much late primary prehnite and penninite.
132	Av.				1.691	55				19/65	81/35	-	7.9	0.32	29.6	t.	56.8	-	-	0.1	4.2	1.4		
133	100									15/47	85/53													Section 20, Facies of gabbro near outer margin of widest part of the gabbro ring.
134	101									15/100	85/0	-	t.	-	23.9	1.1	72.1	-	-	1.9	1.0	-		
135	14									36/72	64/28	-	0.3	-	22.9	1.2	60.9	3.8(1)	7.3	1.1	2.5	-		(1) Sanidine
136	Av.											-	0.1	-	23.4	1.2	66.5	1.9	3.6	1.5	1.8	-		

Table 1. Continued (6)

Item No.	Specimen No.	Olivine Ny	Olivine Fo	Olivine Fa	Augite Ny	Augite 2V	Augite Ca	Augite Mg	Augite Fe	Orthopyroxene Ny	Orthopyroxene En	Orthopyroxene Fs	Plagioclase Ab	Plagioclase An	Mode: Olivine	Mode: Augite	Mode: [illegible]	Mode: Hornblende	Mode: [illegible]	Mode: [illegible]	Mode: [illegible]	Mode: [illegible]	Mode: [illegible]	Mode: Ore	Mode: *	*Mineral in Starred Column	Remarks
																											Section 21. [illegible]
137	359				1.692	52	43	40	17				7	93	-	55.2	0.7	36.6	-	6.9	-	-	-	0.6	-		
138	360				1.693								5	95													
139	356												27	73	-	13.7	30.6	-	-	41.8	-	12.7	0.2	1.0	-		
140	230												28/62	72/38	-	1.3	7.5	42.5	0.6	45.3	-	-	-	2.8	-		
141	222												28	72													Abundant coarse anhedral [illegible]
142	Av.				1.692	52	43	40	17				19/62	81/38	-	23.4	12.9	26.4	0.2	31.3	-	4.2	0.1	1.5	-		
																											Section 22. Inclusions in [illegible]
143	284	1.698	77.5	22.5	1.690				14.5	1.687	81	17			11.1	t.	6.0	77.5	-	4.7	-	-	-	0.7	-		Hornblende Ny = 1.658
144	138				1.695				19						-	26.0	-	43.0	-	26.1	-	-	-	2.9	-		Hornblende Ny = 1.657
																											Section 23 Inclusions in [illegible]
145	358	1.715	69.5	30.5	1.692	52	43	40	17				7	93	4.5	13.0	0.1	60.3	-	20.1	-	-	0.1	[illegible]	-		
146	313				1.692					1.701	70	30	16	84	-	4.7	6.9	15.0	-	60.2	-	-	1.8	11.4	-		
147	115				1.701								18	82	-	40.4	-	1.4	-	54.5	-	-	-	3.7	-		
148	95				1.698								21	79	-	10.3	-	64.1	-	24.9	-	-	-	0.6	-		
149	15												28/33	72/67	-	0.5	-	43.7	-	49.2	-	-	-	6.6	-		
150	94												35	65													
151	101												49/70	51/30	-	3.8	-	68.5	0.1	24.9	-	-	-	0.8	19	chlorite	
152	Av.	1.715	69.5	30.5	1.696	52				1.701	70	30	25/52	75/48	0.7	12.1	1.2	42.2	t.	39.2	-	-	0.3	4.0	0.3		

Table 2. (Con .)

Explanation for column numbers

Column No.	Rocks for which data is given
A	Dunite, free of augite, from core of complex.
B	Augite dunite, contains less than 12.5 percent augite.
C	Augite dunite, from dikes and outlying masses in olivine augitite.
D	Wehrlite, 12.5 percent to 50 percent augite.
E	Wehrlite, from dikes and tabular masses in olivine augitite and dunite.
F	Olivine augitite, contains more than 12.5 percent and less than 50 percent olivine.
G	Olivine augitite, containing more than 12.5 percent olivine, from dikes cutting olivine augitite that contains lesser percentages of olivine.
H	Olivine augitite, contains less than 12.5 percent olivine.
I	Olivine augitite, average of modal values given in columns F and H for normal olivine-rich and olivine-poor facies of olivine augitite.
J	Wehrlite, facies of complex found locally at outer margin of peridotite in direct contact with granulitized country rocks.
K	Olivine augitite, relatively rich in olivine, a facies found locally at outer margin of peridotite in contact with granulitized country rocks.
L	Gabbroic pegmatite, from dikes and irregular masses in olivine augitite.
M	Augite-andradite garnet rock, from dike-like body cutting olivine augitite.
N	Olivine beerbachite, from dikes cutting olivine augitite.
O	Beerbachite, free of olivine, from dikes cutting olivine augitite.
P	Hornblendite-beerbachite, from dike cutting olivine augitite.
Q	Feldspathic vein material, from early primary joints cutting olivine augitite.

Table 2. (Cont.) Explanation for column numbers

Column No.	Rocks for which data is given
R	Olivine gabbro, from parts of gabbro ring near contacts with peridotite.
S	Olivine gabbro, from parts of gabbro ring near contacts with granulitized country rocks.
T	Gabbro, augite gabbro free of olivine.
U	Gabbro, average gabbro obtained from averaging modal values in columns R, S, and T.
V	Gabbro-diorite, facies of gabbro ring from outer margins of widest part of the gabbro ring.
W	Gabbroic streaks and apophyses present in indistinct bands or distinctly cross-cutting dike-like bodies in granulitized country rocks near contacts with the main body of gabbro of the complex.
X	Inclusions of granulitized and amphibolitized country rock in gabbro.
Y	Gabbroic granulite, from granulitized country rocks within a few hundred feet of the outer contacts of the complex.
Z	Hornblende dolerite porphyry, from a partially amphibolitized dike older than the complex cutting lower Silurian conglomerate.
ZZ	Andesite-basalt melaphyre, from a group of Tertiary dikes that cut all the older rocks in the Blashke Islands.

interstitial *calcic plagioclase* which may or may not be altered. Both fresh and altered *plagioclase* are *white*. *Some* accessory interstitial pyrite is not uncommon. Magnetite may *be present* in secondary spongy masses and veinlets that are not detectable megascopically. If uralitic hornblende is abundant it gives the rock a dull, gray-green cast. As the rock approaches wehrlite in composition the weathered surface assumes a mottled or streaky appearance with brown to buff areas of olivine and serpentine contrasting with the green pyroxene.

Under the microscope most slides of olivine augitite are seen to be fairly simple in texture and composition, consisting of coarse pyroxene which may be quite fresh or partially altered to green hornblende and coarse olivine which is locally fresh but normally partially altered to yellow antigorite. However, the textural relationship of olivine to pyroxene appears to be the reverse of that found in the augite dunite, in which augite is clearly interstitial to olivine. In olivine augitite the olivine is commonly interstitial to the augite. It commonly occupies irregular areas between grains of pyroxene which tend to exhibit imperfect crystal form against the olivine, and where the fayalite content of the olivine reaches about 18 percent or more, rounded inclusions of augite are not uncommon in the olivine as shown in plate 17A and 17B.

Textural and compositional variants are more extreme and more common in the olivine augitite than in the other peridotites. There are streaks and bands within the olivine augitite that are mineralogically nearly identical but contrast sharply in texture, ranging from extremely coarse rock with pyroxene grains several centimeters in cross section to relatively fine-grained rocks with grains a few millimeters in section.

Near the outer border of the complex four additional late primary phases appear sporadically in the olivine augitite. These are common hornblende, tremolite, calcic plagioclase (An93 to An96), and rare traces of hypersthene. All of these minerals are clearly later than the augite and most of the olivine and typically appear as single isolated grains occupying interstitial spaces or as coarse textured, irregular streaks or clusters of grains. An unusual facies of the olivine augitite is represented by specimen 133B, item 45, section 4, table 1, page 27. This rock is a wehrlite with moderately abundant late primary hornblende pleochroic in brownish-pink to pale green like hypersthene. Plate 18A is a photomicrograph of this mineral enclosing subhedral olivine. Near the outer margins of the olivine augitite, olivine is found locally enclosing what appears to be primary hornblende as well as hornblende pseudomorphic after augite, as shown in plate 18B.

Modes for olivine augitite in which olivine exceeds 12.5 percent are given in section 6 of table 1; for olivine augitite with less than 12.5 percent olivine in section 8 of table 1; and for an olivine-rich augitite found in contact with gabbro and hornfels at the outer contact of the pyroxenitic ring of the complex in section 10 of table 1. The averages of these modes are recapitulated in columns F, H, I, and K of table 2, and a chemical analysis is given in column I.

Peridotite dikes

All of the peridotitic rocks described above, with the exception of dunite absolutely free of augite, have been found as dikes or veins cutting each other. Well-defined dikes of augite dunite cut dunite, wehrlite, and olivine augitite. Wehrlite and wehrlitic olivine augitite dikes cut dunite, augite dunite, and olivine augitite. Moreover, thin dikes of almost pure augite cut the more olivine-rich rocks. An augite dunite dike cutting massive olivine augitite is shown in plate 5, and several olivine augitite dikes cutting dunite are shown in plate 6. Well-defined inclusions of augitite from mere clusters of a few augite crystals to masses several yards in section have been observed in wehrlite near augitite contacts. Many dikes of olivine-rich rocks such as augite dunite and wehrlite have been found cutting olivine-poor augitite as much as 1,000 feet from the main dunite mass. Thus the contact relationships between the major ultrabasic rock types range from gradational to sharply intrusive.

Modes for augite dunite dikes and outlying bands within the olivine augitite are given in section 3 of table 1; for wehrlite dikes in section 5 of table 1; and for olivine-rich augitite dikes in section 7 of table 1. The average modes are recapitulated in columns C, E, and G of table 2, and chemical analyses of an augite dunite dike and a wehrlite dike are given. The augite dunite dike cuts olivine augitite and the wehrlite dike cuts dunite.

Dike rocks and minor variants associated with peridotite

A distinctive group of dike rocks beside the dikes belonging to the major members of the peridotite complex is found in the peridotite portion of the Blashke Island complex. These rocks form small dikes, generally a fraction of an inch to several inches in thickness and none of mappable size. They are not abundant enough any place in the complex to form an appreciable volume of the rock, but they are quite common everywhere except in the interior of the dunite core of the complex.

In the marginal portions of the dunite core, at a maximum of 1,000 feet from the augitite contact, and generally in augite dunite or wehrlite border facies rocks, there are thin veins or dikes of coarse augite similar to the augite present in the rock. These bodies range from a fraction of an inch to an inch or two in thickness and may be continuous for lengths of up to fifty feet. Commonly the crystals of augite in these bodies are in random orientation, but as large in cross section as the width of the dike. These bodies are generally bordered by a zone of clear yellow serpentine and contain masses of serpentine within them that may represent pseudomorphs after olivine. A modal determination is given as item 96 of section 11, table 1.

Another group of dikes corresponds in composition to major peridotite members but is characterized by a distinctive fabric. These dikes consist of varying proportions of olivine and augite ranging from augite dunite to olivine rich augitite. The texture is granular and finer grained than the typical peridotite of corresponding composition. The augite grains are generally larger than the olivine, while the olivine forms small granular stringers surrounding pyroxene grains and clumps of grains in an anastomosing network, giving the rock a reticulated fabric of granular olivine. Plate 19A is a photomicrograph of a dikelet of this type 1.8 mm wide cutting coarse dunite. These dikes are found in all the peridotite members of the complex but only in the marginal portions of the central dunite core. Where found in dunite and augite dunite these dikes are generally richer in pyroxene than the enclosing rocks, and in wehrlite and olivine augitite they are generally richer in olivine. Their contacts with the enclosing rock may be sharp and defined by a thin zone of serpentine, or the contacts may be distinguished only by an abrupt change in texture, fabric, and relative proportions of constituent minerals. These dikes are also characterized by a relative lack of serpentinization. They range from a fraction of an inch to several inches in thickness and are typically uniform in thickness and attitude for exposed lengths up to 20 or 30 feet.

A distinct group of dike rocks characterized by the presence of calcic plagioclase and primary hornblende is found in the olivine augitite ring of the complex. These rocks are allotriomorphic to hypidiomorphic granular in texture and fine grained, though some contain coarse olivine phenocrysts and large poikilitic hornblende crystals and are thus porphyritic (Photomicrograph, plate 19B). The typical texture may be described as aplitic. They are gabbroic in composition ranging from wehrlite, with a small amount of calcic plagioclase and no primary hornblende, to hornblendites containing minor calcic plagioclase (Photomicrograph, plate 20A). They have the following mineral assemblages and characteristics:

1. Olivine, augite, plagioclase, and only late poikilitic hornblende.
2. Olivine, augite, plagioclase, and primary hornblende.
3. Augite, plagioclase, and hornblende, with a little olivine surrounded by enstatite-actinolite coronas.
4. Augite, plagioclase, and hornblende, with traces of hypersthene in a few specimens.

5. Hornblende with minor plagioclase and traces of augite and hypersthene.

The dikes of this group also range from a fraction of an inch to a few inches in thickness and are uniform in thickness and attitude for exposed lengths of up to 30 feet. Their contacts with the enclosing rock are sharp and usually marked by a narrow zone of hornblende. Some dikes of this group exhibit distinct flow fabrics with the minerals in streaks and with strong preferred orientation parallel to the walls. Dikes of groups 4 and 5 are also common, cutting the gabbro ring of the complex.

The name beerbachite was coined by Chelius (1892, pp. 2-4) for rocks described as "gabbro-aplite" but containing a substantial percentage of mafites. The name issite was applied by Duparc (Duparc and Grosset, 1916, pp. 106-108) to a hornblendite with subordinate clinopyroxene and less calcic plagioclase found in dikes cutting dunite. It seems undesirable to use a number of names for different variants of a genetically related sequence of rocks where the use of different names merely obscures the essential consanguinuity. Therefore the name beerbachite will be used to refer to these rocks as a group, and it will appear from the discussion of the origin of these rocks in a later section that this name may be peculiarly appropriate in the light of the controversy that has taken place over the origin of the beerbachites from the type locality.

Modes are given in sections 14 and 15 of table 1. The beerbachites of section 14 contain substantial percentages of olivine and those of section 15 are free of olivine. The averages are recapitulated in columns N and O of table 2. An analysis of hornblende-rich, olivine-free beerbachite (specimen 99, item 112, section 15, table 1) is given under column P of table 2.

One unusual dike-like body associated with dikes of this group consists of an aplitic textured, fine grained, white rock composed of almost colorless granular diopsidic augite and colorless andradite garnet with a little chlorite. The mode of this rock is given as item 103, section 13, of table 1 and in column M of table 2. A chemical analysis and calculated norm is given under column M of table 2. (Photomicrograph, plate 20B) The mineralogical and chemical composition make it almost certain that this is a rock produced by contact metamorphism of a limestone and raises the question as to whether it is an inclusion rather than a dike. The field relations are quite clear. The rock is exposed continuously for several yards as a dike about 3 inches wide cutting coarse olivine augitite. The walls are sharp and parallel and several small, altered, angular inclusions of olivine augitite are present near the walls of the dike. Although a product of contact metamorphism, it has certainly been completely "mobilized." _/

The possible significance of this dike will be taken up again when the origin of the beerbachites is discussed.

Within the olivine augitite ring of the complex, and particularly near its outer border, are irregular masses and dike-like bodies that might be described as basic pegmatite. They are characterized by very coarse calcic plagioclase with coarse hornblende, augite, olivine, and spinel. In some specimens the olivine is surrounded by coronas of enstatite and actinolite. In others no trace of corona formation is present. Some of these bodies are merely formless, irregular patches within the augitite; others are distinct dike-like bodies with sharp contacts with the augitite; while a box-work pattern of pegmatitic streaks in coarse olivine augitite is developed in other places. These relations are shown in photographic plates 7, 8, and 9. Some of the dike-like bodies show a crude zoning, tending to be feldspathic toward the center with elongated hornblende crystals growing from the walls inward. The dike-like bodies range up to several feet in thickness but none are exposed for more than a few tens of feet. Most of the irregular masses are only a few inches in cross section, but they may contain anorthite crystals an inch across, generally concentrated in the center of the mass. Mineralogical data for some basic pegmatite specimens is given in section

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_/ A euphemism employed when a petrologist does not quite have the courage to say fused or dissolved.

12 of table 1, and a chemical analysis of a composite specimen is given under column L of table 2.

Gabbroic rocks

Gabbro

The gabbro of the Blashke Island Complex ranges widely in mineralogy, texture, structure, and field relations. The essential components are plagioclase, augite, and hornblende. The gabbro tends to be rich in augite near the inner margin of the ring where almost all of the hornblende has late poikilitic relations to augite and plagioclase. Toward the outer margin of the gabbro, augite is much less abundant and in most facies largely replaced by hornblende. Here the rock also contains a good deal of primary hornblende. Olivine is commonly present in the gabbro near contacts with peridotite and absent in the outer portions. Hypersthene and biotite are present locally and in small amounts in the outer parts of the gabbro, generally near hornfels contacts. Common accessories are apatite, sphene, and ores - including sulfides, magnetite, and ilmenite. Prehnite and pennine appear sporadically as late interstitial primary minerals and as alteration products. Other common alteration products and fracture fillings are zoisite, clinozoisite, epidote, leucoxene, tremolite-actinolite, sericite, clay minerals, heulandite, and carbonates. Quartz is present as a late interstitial primary mineral in a facies of the gabbro mass at the outermost contacts with country rocks, and late interstitial sanidine or albite is found locally in this facies. A deep golden garnet is found as one of the principal primary minerals in a coarse gabbroic veinlet cutting into a large hornfels inclusion within the gabbro. Modes and data on the composition of the major minerals of the gabbro are given in table 1. Section 17 of table 1 gives data on olivine gabbro, section 18 on typical augite gabbro free of olivine, and section 19 on facies of the gabbro near the outer contacts. These modes are recapitulated in columns R, S, T, V, and W of table 2 and a chemical analysis of a composite specimen of the gabbro is given in column U.

Where augite is in large excess of plagioclase in the rock near the inner contacts of the gabbro ring, it is distinctly earlier than plagioclase and commonly present as inclusions showing some semblances of crystal form in large interstitial grains of plagioclase. Where the plagioclase is approximately equal in volume to augite the two minerals are mutually interfering and appear to have crystallized simultaneously. Toward the center and outer portions of the wider parts of the gabbro ring where plagioclase is in large excess of augite, the augite is distinctly later than plagioclase and is commonly poikilitic, enclosing numerous subhedral grains of plagioclase. The olivine is found in scattered, anhedral grains, many of which enclose rounded grains of both augite and plagioclase. Olivine is apparently somewhat later than at least part of the pyroxene and feldspar. The olivine in some of the gabbro has coronas of several types and these will be described on pages 134-8. Hornblende is commonly later than the other primary silicates and much of it has formed by the replacement of the other silicates, but mainly of augite. However, some small inclusions of hornblende with crystal form can be found locally in augite, indicating a small amount of primary crystallization of hornblende along with augite. Of the accessories, apatite formed early, but sphene and the sulfide and oxide ores crystallized late and commonly replace all primary silicates including hornblende.

The texture of the gabbro is coarse and varied, ranging from allotriomorphic to hypidiomorphic granular. In outcrop the mafic minerals weather dark and the feldspar white or pale brown, while on fresh surfaces the mafites are black or dark green and the feldspar white, so that there is commonly little difference in color between fresh and weathered surfaces. A striking feature of much of the gabbro is a thin layering or banding caused by the concentration into closely spaced parallel layers of most of the late, poikilitic hornblende. The width of bands relatively rich or relatively poor in hornblende ranges from a fraction of an inch to a couple of inches, and the extent to which this texture is developed ranges from strong to very subdued, grading into uniform gabbro with an almost granitic texture. The layering is accompanied by a slight to distinct preferred orientation of tabular plagioclase crystals toward parallelism with the banding.

The banding is steeply dipping almost everywhere that it is present, but the strike does not show any very consistent orientation or relationship to the pattern of the complex except that near both the outer and inner contacts of the gabbro it tends to swing into parallelism with the contacts, but may also be found locally at high angles to the contacts with hornfels. The banding does not maintain a consistent and uniform attitude over stretches of many yards, but is commonly wavy to strongly contorted and presents a remarkable pattern of sets of sweeping curves transecting and transected by other sets of curving bands. The surfaces of intersection between cross-cutting sets of bands are almost all steeply dipping. Plates 10 and 11 depict some striking examples of this structure. Figures 3, 4, 5, and 6 are pen sketches of some of the patterns displayed by the banding.

It is important to note that this layering is not due to the segregation of two early primary phases into layers alternately enriched in one mineral or the other with the residual liquid crystallizing at random interstitially or by deuteric reation. The layering is due to the concentration of hornblende, the last important component of the rock to form, into relatively enriched bands with respect to plagioclase and augite, the earliest important components of the rock to crystallize. The plagioclase shows some evidence of fluidal orientation and in some slides there appears to be a little protoclastic breaking and rounding of the larger plagioclase crystals, but the hornblende forms coarse, irregular, completely anhedral poikilocrysts enclosing randomly oriented, somewhat rounded grains of plagioclase and augite and has grown at least partly at the expense of plagioclase and augite. Apparently the texture formed by the concentration into these bands of a late fluid phase that reacted with the solid phases to form hornblende.

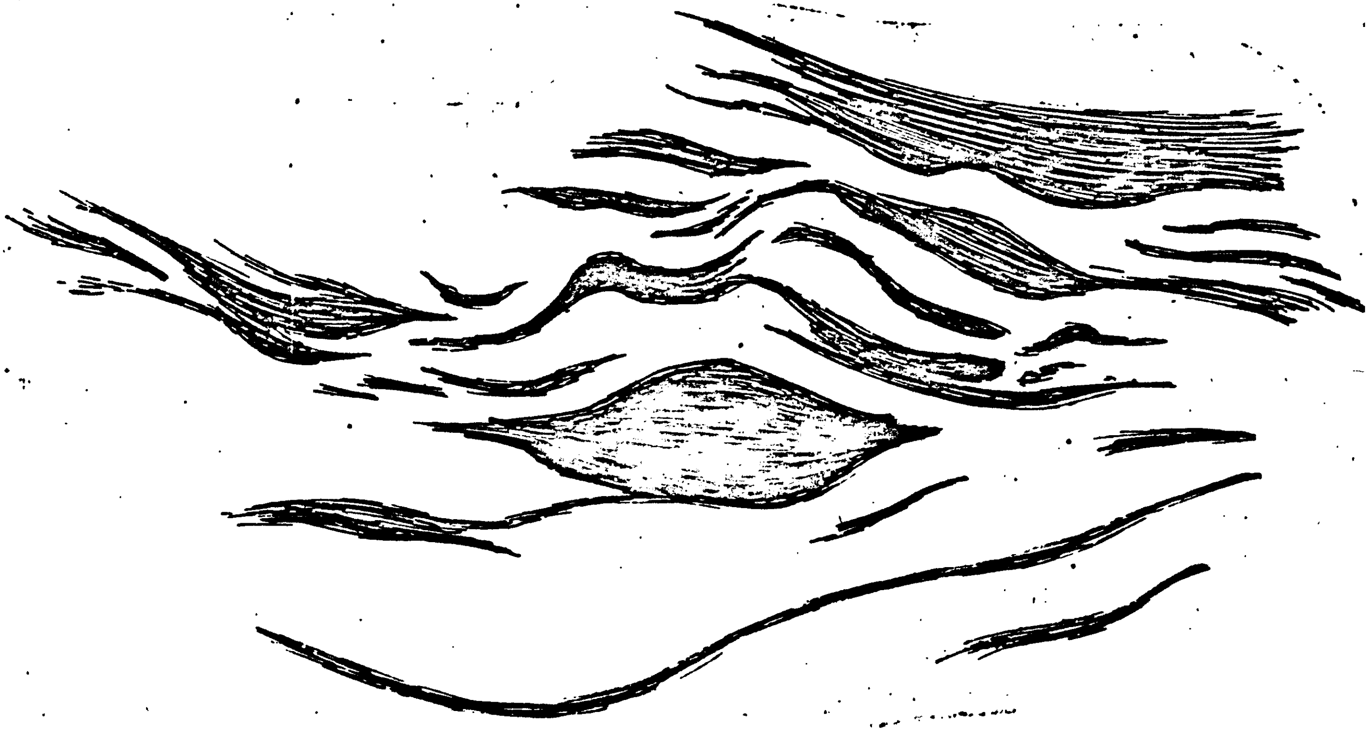

Figure 3, Pen sketch showing trend and pattern of hornblende-rich bands in gabbro. This pattern is shown on a nearly horizontal outcrop surface. The bands are steeply dipping. The length of the outcrop is about ten feet.

Figure 4, Pen sketch showing trend and pattern of intersecting and converging hornblende-rich bands in gabbro. The outcrop surface is nearly horizontal and about 6 feet long. The bands are steeply dipping.

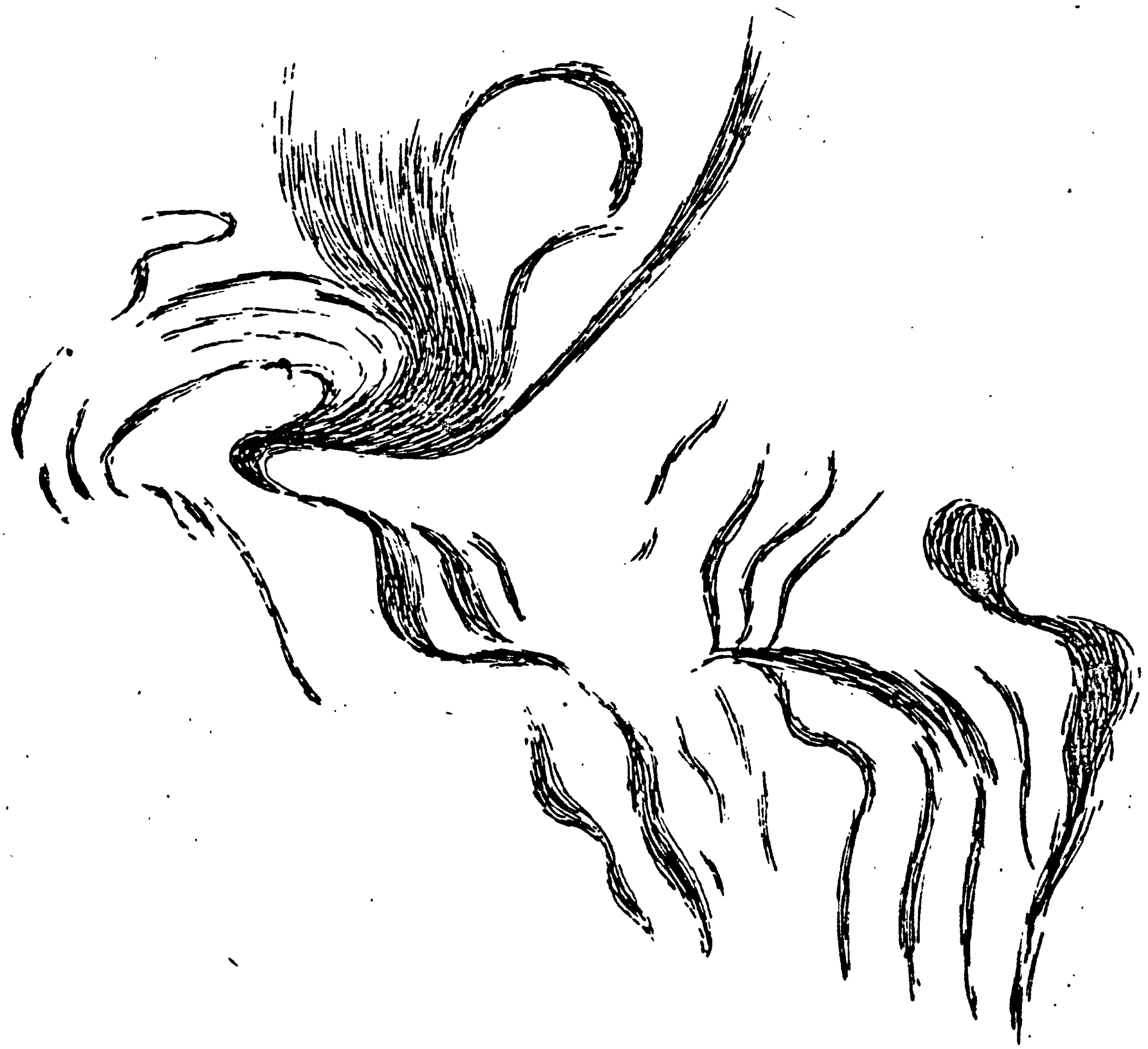

Figure 5, Pen sketch showing trend and pattern of swirling hornblende-rich bands in gabbro. The outcrop surface is nearly horizontal and about 4 feet long. The bands are steeply dipping.

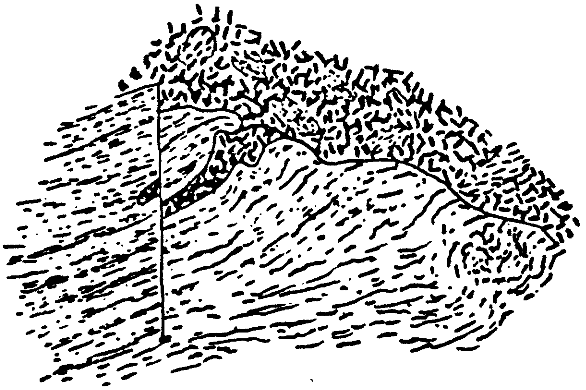

Figure 6, Pen sketch showing trend and pattern of hornblende-rich bands in a relatively light-colored, even-textured gabbro cut by a coarse, mafic gabbro containing numerous inclusions of lighter-colored gabbro and hornfelsed country rock. Both gabbros are cut by a small slip. The outcrop surface is nearly vertical and about 3 feet long.

In a few localities, where the gabbro does not have the layered or banded texture, it has a mottled or spotted aspect due to the concentration of a larger percentage of late hornblende into more or less equant clusters from an inch to several inches in section separated from adjacent clusters by gabbro containing a smaller percentage of hornblende. However the common texture where not banded is coarse, uneven, and almost granitic.

A peculiar and not fully understood feature of the exposure of the Blashke Island complex is the fact that nowhere is there a fully exposed contact between the main olivine augitite ring and the main gabbro ring. In fact an inspection of the geologic map (plate 1) will show that the erosion of the sea-ways in the Blashke Islands has been controlled by this contact more than by any other feature. The gabbro-peridotite contact apparently is a zone of extremely weak resistance to erosion. For a distance of about 1,400 feet along the easternmost border of the peridotite mass the contact with gabbro traverses "dry land", but even here the contact is concealed beneath a narrow strip of swampy ground except for a partial and imperfect exposure at the southern end. At the partly exposed part of this contact there are almost continuous outcrops of uniform olivine augitite up to a covered area of low ground forming an indentation at the head of the small bay where the outcrop is located. East of this break in the exposure is a facies of the olivine augitite that contains 4 or 5 percent of interstitial anorthite (specimens 215 and 216, items 81 and 83, section 8, table 1) and this appears to pass rather abruptly in a distance of 10 or 20 feet into a coarse, mafic, olivine gabbro with about 36 percent anorthite (specimen 219, item 119, section 16, table 1). Within the feldspathic olivine augite there appeared to be some small inclusions of gabbro, but none of these could be broken from the outcrop for investigation.

On the north side of the channel north of the long island forming the east shore of Bivouac Bay there is a somewhat similar relationship exposed. South of the channel is a normal olivine augite. North of the channel is a thin band of olivine augitite (specimen 261, item 80, section 8, table 1) containing numerous irregular streaks and bands of coarse, anorthite-bearing basic pegmatite that passes within a few feet northward into a fine-grained granular augitite almost free of olivine and with a little interstitial feldspar. This feldspathic augitite, which is by no means close to normal gabbro in composition or texture, is in direct contact with hornfelsed country rock (specimen 253, item 156, section 22, table 1).

An entirely different relationship is exposed on the south side of the small gabbro mass (specimen 142, item 118, section 16, table 1) surrounded by olivine augitite near the eastern border of the olivine augitite ring. Here one exposed contact is perfectly sharp between the two rocks and the contact surface has several angular irregularities in it and some small apophyses of gabbro tonguing out into the olivine augitite. In places this contact is marked by an open joint between the two rocks. At another place a hornblendite dike about 2 inches wide follows the contact for a few feet. Unfortunately, a low angle, westward dipping, fault surface forms the other exposed contact with olivine augitite and the exact relationship of this body of gabbro to the main gabbro ring of the complex remains a matter of speculation.

To summarize the contact relations between the gabbro ring and the olivine augitite shell of the peridotite complex; one contact between the main masses of both rocks is abruptly gradational from a slightly feldspathic facies of the olivine augitite into a coarse, olivine gabbro. A gabbro mass that is present within the olivine augitite ring, possibly as the result of faulting, has sharp intrusive relations with the olivine augitite, and at a third contact, a slightly feldspathic augitite, is in direct contact with gabbroic hornfels. However, there is reason to believe that none of these exposures are typical of most of the contact, because most of the contact has proved peculiarly nonresistant to erosion while these contacts are of normally resistant rock. Furthermore none of the contacts, where exposed, affords a view of the transition from a feldspathic facies of the olivine augitite into the normal olivine augitite in which feldspar is very sparsely and sporadically distributed.

The contacts between gabbro and country rocks are exposed at many points around the periphery of the complex. They range from sharply intrusive in character where the gabbro ring is broad, to vaguely demarcated transition zones a few feet wide between gabbroic rock with irregular texture and gabbroic granulite cut by numerous irregular dikes and streaks of rock with coarse but not typical gabbroic texture. In some places, as shown in plate 12, a clear-cut intrusion breccia marks the contact. Tongues of gabbro enmesh numerous angular blocks of hornfelsed country rock. This type of contact is best exemplified locally around the northeastern and eastern border of the complex where the gabbro ring is widest in outcrop. At other points, particularly around the southwestern and western part of the complex where the gabbro ring is narrow and less perfect, a more irregular and less distinct type of contact is developed. Here many tongues and apophyses of gabbro pass off into country rock, but they tend to be irregular in width and attitude and to fade out into coarse gabbroic hornfels that is difficult to tell in the field from the gabbro. Inclusions in this part of the gabbro are commonly indistinct and rounded or irregular in shape rather than angular.

A conventional interpretation of the field relations of much of the gabbro around the western edge of the complex probably would lead to the conclusion that there has been a great deal of brecciation and partial assimilation of country rock by gabbroic magma in certain localities. However, gradational relations between gabbroic granulites of undoubted metamorphic origin and irregular streaky zones of coarse-grained rock of gabbroic composition but with suggestions under the microscope of porphyroblastic texture, argue that much so-called gabbro has been derived by recrystallization of hornfelsed country rock. After all, the same mineral phases are present in both the gabbro and the gabbroic granulite hornfelses. Only the textures, and to a lesser degree the proportions of constituents, are different. The chemical compositions of gabbro and gabbroic granulite are strikingly similar as shown in columns U and Y, table 2. Gabbros with dubious textures and relations suggesting derivation by recrystallization and replacement of country rocks are represented by specimens 308, 309, 347, 358, 360, 356, and 230, items 122, 124, 123, 138, 134, 140, and 141, table 1.

Many dikes ranging in size from small gabbroic stringers to masses of coarse gabbro 200 feet wide and exposed for distances of over 1,000 feet cut the country rock within one to two thousand feet of the main complex, and their contacts are typically sharp but not characterized by chilled borders.

Throughout the gabbro mass angular to rounded or streaky inclusions of mafic, amphibolitic granulite are common. Plate 13 shows an outcrop of gabbro near the inner part of the broad northeastern section of the gabbro ring containing numerous angular inclusions. The gabbro is also cut by numerous mafic hornblende-augite-plagioclase dikes of the beerbachite group, and locally masses of this type brecciate the gabbro and contain inclusions of gabbro. A hornblendite-beerbachite dike is cutting the gabbro in plate 13. Despite the distinctly different modes of occurrence of the inclusions in the gabbro and the dikes cutting the gabbro, they correspond rather closely in composition. The modal mineral composition of inclusions and dikes in gabbro can be compared in section 23 of table 1. Specimens 95 and 15 , items 148 and 149 are dikes and the other specimens are angular inclusions.

Gabbroic granulite

The country rocks surrounding the Blashke Island complex show evidence of contact metamorphism for distances up to a thousand feet. Near the complex, contact metamorphism is generally strong to extreme and the country rocks have been transformed into granular hornfelses of gabbroic to amphibolitic composition in a zone one hundred to two hundred feet wide. Similar rocks formed by the thermal metamorphism of basaltic lavas were called "granulitic gabbro" by Geikie and Teall

(1894, p. 647 and pp. 650-651) and this term was continued in use by Harker (1904, p. 115) who stated that the term was equivalent to "pyroxene granulite" as used by continental European petrographers. The name granulite has long been applied to a variety of metamorphic rocks with a crystalloblastic-granular texture (Rosenbusch, 1910, pp. 622-626). Since the rocks are not gabbro in the genetic sense, but are of gabbroic composition and mineralogy, the name "gabbroic granulite" will be employed rather than "granulitic gabbro."

The gabbroic granulites characteristically weather to a hard, smooth, brownish-black to reddish-brown surface. Coarser streaks with gabbroic texture have a mottled surface because the calcic feldspar tends to weather white or pale brown. Nodular clusters and streaks of mafic minerals tend to stand out in relief and weather black. Jointing is generally very irregular both in spacing, attitude, and patterns of sets. In fact it is difficult in most outcrops to discern any well-defined joint sets. Some primary structures and textures of the original sedimentary or volcanic rock are locally etched out as clearly by weathering as though the rock had undergone no metamorphism. Thinly laminated bedding and conglomeratic textures are clearly shown on the weathered surfaces of some outcrops, but elsewhere obliterated or almost obliterated. Freshly broken surfaces of the granulite range in color from light to dark gray with a brownish cast if biotite or hypersthene is abundant. The fresh surface has a granular, sugary texture. Most granulite is too fine-grained for any individual minerals to be recognizable in hand specimen except for grains of sulfides, but in coarser specimens it is commonly possible to recognize biotite, plagioclase, and perhaps hypersthene, if present.

Under the microscope the gabbroic granulite is seen to have typically a crystalloblastic granular texture formed by a mosaic of plagioclase through which small, more or less equidimensional grains of augite are scattered. Plate 21A shows this texture in its simplest form. If olivine is present it is generally in relatively coarse anhedra that are commonly strikingly poikilitic, enclosing numerous plagioclase, and augite grains as shown in plate 21B. Hypersthene, if present, is commonly in anhedral grains but noticeably elongated in the direction of the c axis. Biotite, if present, is generally distributed through the rock in irregular clusters of unoriented flakes generally associated with grains of olivine, hypersthene, or ore.

The most intensely metamorphosed facies of the gabbroic granulite are found at the localities on the northern and western borders of the complex where peridotites are in contact with country rocks without any intervening gabbro. Here the country rocks have been converted into dense, fine-grained to moderately coarse-grained rocks consisting primarily of a granular aggregate of calcic plagioclase and augite, but generally containing in addition substantial percentages of either olivine (hyalosiderite) and biotite, hypersthene and biotite, or hypersthene. Both sulfide and oxide ores are present, and apatite in coarse, anhedral grains is an ubiquitous accessory. Modes and mineralogical data for granulites of this facies are given under section 24, of table 1, and the modes are averaged under column Y of table 2, and an analysis and calculated norm is given.

In spite of the complete mineralogical transformation and recrystallization that has taken place in the gabbroic granulite, original structures and textures such as bedding and conglomeratic or agglomeratic textures are locally distinctly visible in outcrop, hand specimen, and thin section. Thus the outcrop from which specimen 368, items 161 and 162, table 1, came has the aspect of a coarse boulder conglomerate composed of rounded pebbles, cobbles, and boulders that stand out both on weathered and broken surfaces from their matrix. Plate 22A is a photomicrograph of the matrix of this rock. In thin section there is no break in the granular mosaic texture between the pebbles and the matrix, but there is an abrupt difference in the mineralogy as is shown by the modes given in table 1 for the matrix and the pebbles, though both have clearly undergone complete mineralogical transformation from their probable original composition. In the outcrop of specimen 280, items 157 and 158, table 1, there are several nodular masses an inch to two inches in cross section with a finer texture and lighter color than the rest of the rock that appear in cross section to resemble fossil mollusca. However their original fossil nature cannot be proved due to the extreme alteration, and they may just as well be relicts of concretions, pebbles, inclusions in a volcanic rock, or large amygdules. They have been converted into an augite-plagioclase granulite closely comparable to that of the pebbles in specimen 368, while, as in specimen 368, the groundmass contains olivine and biotite. Plate 21B shows the host rock of specimen 280, and plate 21A shows the enclosed nodule of dubious fossil origin. Mineralogical differences reflecting compositional differences in original bedding are shown by specimen 285, item 159, table 1. The part of the rock from which the section was cut for which the mode is given in table 1 contains hypersthene almost to the exclusion of augite. An adjacent band in rock contains augite and virtually no hypersthene or biotite.

Grout (1933, pp. 989-1040) has described gabbroic granulite derived from slates that have been gabbroized by contact with the Duluth gabbro. The slates are shown to have been changed to rocks approaching gabbro in both mineralogy and chemical composition by the addition of lime and magnesia and the driving out of other components and by complete recrystallization. In the Blashke Island complex gabbroization is even more extreme.

Although original structures and megascopic textures are locally well preserved during the metamorphism of the country rocks to gabbroic granulite, they are also progressively obliterated by the onslaught of thermal metamorphism at other points around the complex. As the peridotite mass is approached the texture of the granulite becomes coarser. Indistinct streaks and irregular vein-like bodies with a gabbroic texture appear, as do streaks and coarse nodular masses of mafic minerals. The rock may be interpreted as having been injected by gabbroic magma, but no really clear-cut evidence for anything but progressive reconstitution of country rocks can be found. Specimens 253, 258, and 363, items

155, 154, and 156, table 1, are coarse gabbroic granulites approaching the normal gabbro in texture, but locally showing relict structures such as bedding, and differing from normal gabbro in the presence of such phases as hypersthene and biotite. Specimen 266, item 153, table 1, is from a coarse mafic nodule a few inches in cross section in the outcrop a few yards from where specimen 280 was taken. This rock is a coarse, feldspathic websterite mineralogically.

The intensity of metamorphism drops off noticeably within a few tens to a hundred feet of the complex. Olivine is not present, biotite becomes progressively more abundant, the plagioclase becomes more sodic, and a few hundred to a thousand feet from the complex the rocks pass into normal chloritic and amphibolitic greenstones in which albite, orthoclase, quartz, chlorite, pale green amphibole, zoisite, epidote, and calcite are common phases. Specimen 232, item 169, section 22, table 1, is a laminated hornfels from about 400 feet north of a gabbro-granulite contact at the northeastern edge of the complex. This rock consists of a coarse mosaic of anhedral quartz with coarse subhedral to euhedral crystals of a deep reddish-brown biotite and a green amphibole scattered through it. This assemblage of minerals is riddled throughout by small granules of orthoclase so that the sections of hornblende and biotite resemble slices of an exceptionally vesicular Swiss cheese, while the volume of granular orthoclase in the quartz exceeds considerably the volume of the quartz. Five hundred feet further north the laminated hornfels passes into a low grade greenstone with abundant chlorite and calcite.

The gabbroic granulites developed near gabbro contacts with country rock, particularly where the gabbro ring is wide, show a lesser intensity of metamorphism than the granulites at peridotite contacts. Olivine is not found except in one specimen (358, item 146, section 21, table 1) from an inclusion near a gabbro contact with granulite very close to the peridotite mass. Hypersthene is common and biotite is abundant. The plagioclase is generally in the andesine range.

Inclusions of country rock are very common in the gabbro. Such inclusions are apparently very rare in the peridotite, but two small ones were found within olivine augitite near its outer margins. These inclusions are also characterized by granulitic texture, but they are a distinctly different facies from the gabbroic granulites in external contact with rocks of the complex. They are characterized by the presence of appreciable to abundant hornblende, which is absent in the normal granulites near peridotite contacts, and also characterized by the virtual absence of biotite, which is common in the normal granulites. Modes and mineralogical data on inclusions in olivine augitite are given in section 22, table 1, and on inclusions in gabbro in section 23.

Olivine and hypersthene are not truly typical of the granulitized inclusions present in the gabbro, but olivine and hypersthene are abundant in one of the inclusions in olivine augitite and absent in the other. Plate 22B is a photomicrograph of the olivine-hypersthene hornblendite inclusion, specimen 284, item 144, section 22, table 1. The two inclusions from gabbro that contain these minerals, specimens 358 and 313, items 146, and 147, table 1, are from inclusions in narrow, irregular bodies of gabbro on the western side of the complex where the gabbro is not well developed. The olivine in specimen 358 is coarse, anhedral, and clearly poikilitic with respect to hornblende as well as augite and plagioclase as is shown by the photomicrograph plate 23A. The other specimens of inclusions in section 21 of table 1 are from the broad gabbro mass on the eastern side of the complex and are typical of many specimens of hornblende-rich gabbroic granulite found as inclusions in the gabbro.

Modes and mineralogical data on the host rocks from which the inclusions of specimens 358, 115, and 101 came are given as items 138, 126, and 134, sections 19 to 20, table 1. Comparison shows that the host rock and the inclusion contain essentially the same phases but in different proportions. However, inclusion 358 contains olivine while the host does not, and perhaps paralleling this relationship, the inclusions of 115 and 101 contain a larger percentage of augite, which is their most mafic anhydrous silicate, than do the host rocks. The salient difference between country rock thermally metamorphosed by external contact with the complex and country rock caught up as inclusions in the rocks of the complex is the fact that hornblende is present, or even predominant, in the inclusions and not in the externally metamorphosed rocks for some distance beyond their contacts with the complex. Hornblende is, of course, the characteristic hydrous mafic mineral of both the gabbro and the olivine augitite containing the inclusions.

Mineral phases and their variations in composition

The foregoing description of the petrology of the Blashke Island complex and the numerous micrometric determinations of modal mineral content given in tables 1 and 2 reveal that four minerals combine to form more than 95 percent of each of the major rock types of the complex, if alteration products such as serpentine are considered as representing the primary minerals from which they were derived. These minerals are olivine, augite, plagioclase, and hornblende. Actually much of the hornblende is secondary after augite. The varying proportions in which these mineral phases are combined, together with textural relations and mode of occurrence, define the rock units.

Each of these minerals has a broad range of composition owing to the substitution of one element for another. Iron and magnesium substitute for each other in olivine. Calcium, magnesium, and iron are interchangeable over a wide range in augite. Calcium and aluminum substitute for sodium and silicon in plagioclase. Hornblende is capable of complex substitutions involving calcium, magnesium, bivalent and trivalent iron, aluminum, silicon, and sodium. This brief statement takes account only of the major substitutions commonly encountered. Other elements play a role in one or more of these minerals, but generally a minor one.

It is not surprising, therefore, to find that the relatively simple pattern of variations in mineral make-up of the Blashke Island rocks is complicated by correlated variations in the composition of each of the mineral phases. An attempt has been made to trace this pattern of variation within each mineral phase throughout the complex by the measurement of optical and other properties whose correlations with chemical composition are known.

The sections that follow present a detailed account of the petrographic relations and the data relating to variations in composition of each of the minerals playing a role in the complex. In order to avoid burdening the reader with too much detail and perhaps obscuring some important relationships, a brief resume and synthesis of the more important findings detailed in the sections that follow on individual minerals is given here. Attention is focussed on the mineralogical relationships of petrologic significance especially in regard to the mode of origin of the rocks and the complex as a whole. The reader is referred to the sections on individual minerals for the evidence on which these findings are based, the data and method of investigation, and for clarification of questions concerning the petrographic relations of any given mineral. A particularly lengthy treatment of the problem of serpentinization is given in the section on serpentine, and some data on the problem of coronas is given in the section on coronas and coronites, pages 134 to 138 .

Olivine is a major component of the peridotitic rocks of the complex and is present in some facies of every major rock unit. More than any other phase its variation in composition supplies a unifying thread throughout the complex. In the interior of the dunite core olivine has a composition of Fo90Fa10. The fayalite content increases near the margins of the dunite core, and at the major contact between rocks composed principally of olivine and rocks composed principally of augite the olivine falls in the range Fo87Fa13 to Fo86Fa14. The fayalite content of the olivine present in subordinate percentages in the olivine augitite ring of the complex has a wide range but tends to increase with increasing distance from the dunite core. Beyond the immediate contact between dunitic and augititic rocks no olivine in normal massive peridotite has a fayalite content less than Fo85Fa15, but dikes and outlying masses of augite dunite and wehrlite emplaced within the augitite ring have olivine corresponding in composition to the same rocks in the marginal facies of the dunite core. Near the outer margins of the augitite ring the fayalite content of the olivine ranges as high as Fo74Fa26, but certain wehrlitic facies of the complex in sharp contact with granulitized country rocks have olivine with a much lower iron content, averaging Fo84Fa16. This wehrlite contact facies is undoubtedly not fully representative of an original magma chilled at the contact, but it may give a hint as to the general character of such a magma if it existed. The gabbroic pegmatite, olivine beerbachite, and gabbro range above the augitite in the fayalite content of their olivine, and in the gabbroic granulite the olivine is a hyalosiderite with nearly 50 percent fayalite (Fo51Fa49).

The data on the composition of olivine are given in table 1 for all specimens and summarized in table 3. Figure 7 is a graphical representation of the relationship of the percentage of original olivine in the rock to the composition of the olivine. In this figure the peridotitic rocks are distinguished from the feldspathic rocks by separate symbols, and the composition of olivine correlated with the presence of other phases and with certain paragenetic relationships is noted along the margin. Figure 8 shows the data on the composition of olivine plotted against the relative distance inward or outward from the major contact between rock in which olivine is the major constituent and rocks in which augite is the major constituent. This graph covers only the peridotitic part of the complex. Different rock types are designated by separate symbols and a trend line has been sketched on the graph to show the variation in olivine composition. There is considerable dispersion of values for olivine within the olivine augitite ring, but inspection of the plotted symbols will show that most of the lower-iron olivines are in augite dunite and wehrlite dikes cutting the olivine augitite or in wehrlitic contact facies. The sketched trend line represents the upper limit of iron content reached by olivine in normal massive olivine augitite with increasing distance from the dunite core.

Table 3.

Composition of olivine in peridotites of the Blashke Island Complex.

Rock Type	Composition of olivine	
	Average	Range
Dunite	Fo89.5Fa10.5	Fo90Fa10 - Fo88.5Fa11.5
Augite dunite, marginal facies of dunite	Fo87.5Fa12.5	Fo90Fa10 - Fo86Fa14
Augite dunite, dikes and outlying bodies	Fo87Fa13	Fo88.5Fa11.5 - Fo86Fa14
Wehrlite, marginal facies of dunite	Fo86Fa14	Fo88Fa12 - Fo83Fa17
Wehrlite, dikes and outlying bodies	Fo86Fa14	Fo88Fa12 - Fo83Fa17
Wehrlite, outer contact facies	Fo84Fa16	Fo86.5Fa13.5 - Fo82Fa18
Olivine augitite, olivine-rich	Fo85Fa15	Fo86Fa14 - Fo84Fa16
Olivine augitite dikes, olivine-rich	Fo83Fa17	Fo83.5Fa16.5 - Fo82.5Fa17.5
Olivine augitite, olivine-poor	Fo82Fa18	Fo87Fa13 - Fo80Fa20
Olivine augitite, outer contact facies	Fo78Fa22	Fo81.5Fa18.5 - Fo74Fa26
Basic pegmatite segregations	Fo78Fa22	Fo81Fa19 - Fo75Fa25
Hornfelsed inclusion in olivine augitite	Fo77.5Fa22.5	
Hornfelsed inclusion in gabbro	Fo69.5Fa30.5	
Gabbro	Fo73Fa27	Fo75.5Fa24.5 - Fo70.5Fa29.5
Olivine beerbachite dikes	Fo77Fa23	Fo81.5Fa18.5 - Fo76.5Fa23.5
Gabbroic granulite	Fo51Fa49	

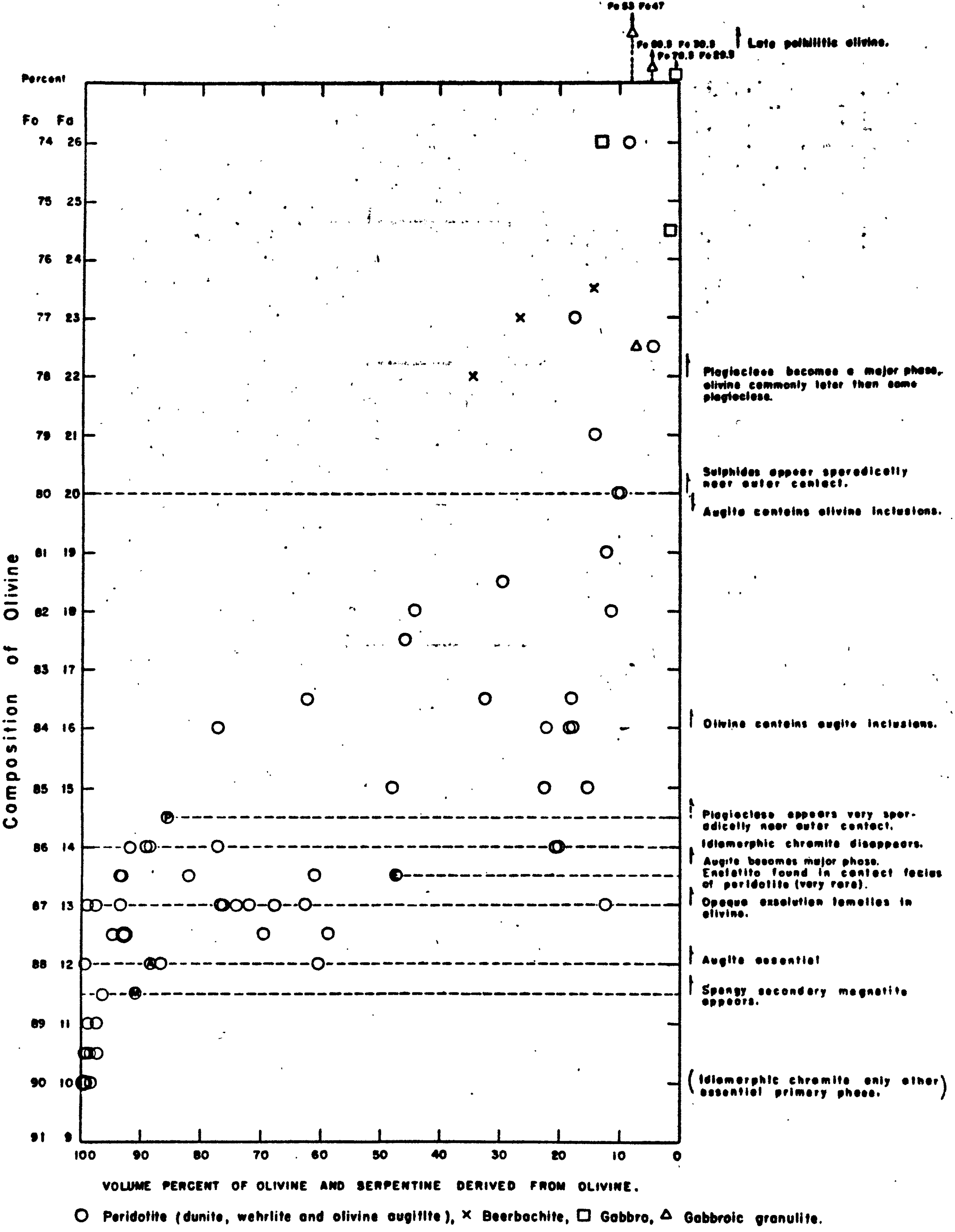

Figure 7, Relationship of olivine composition to modal percentages of olivine plus derived serpentine and to the presence of other phases in Blashke Island peridotites, beerbachite, gabbro, and gabbroic granulite.

The paragenetic relations of olivine change with its change in composition. Forsteritic olivine ranging up to about Fo85Fa15 and present only in and near the core of the complex and in olivine-rich rocks is the first silicate to crystallize and is subject to replacement by augite. Someplace in the range of composition Fo84Fa16 to Fo80Fa20 and in the outer part of the olivine augitite ring this relationship is reversed and augite is the earlier phase. With increasing iron content the olivine appears later and later in the paragenetic sequence and where hyalosideritic it is the last major primary silicate phase to form.

Augite undergoes a shift in composition with increasing distance from the core of the complex paralleling that of olivine. The data on augite is portrayed graphically in figures 9, 10, and 11. Figure 9 shows the composition of augite as determined from optical data in terms of the major bivalent components, calcium, magnesium, and iron. Figure 10 is an enlarged portion of the same diagram with the points indicated by symbols showing the rock type from which the augite came. The average trend in composition of augite from the peridotites, beerbachite and gabbro shows little variation in the percentage of calcium. In these rocks the variation is mainly the substitution of iron for magnesium, but iron in augite from the granulitized hornfels surrounding the complex ranges considerably higher in iron content and there is a substantial substitution of iron for calcium. The trend of variation of augite is summarized in the following table.

Table 4

Average composition of augite in major rock units of Blashke Island Complex.

Rock type	Atomic percent		
	Ca	Mg	Fe
Augite dunite	48	45	7
Wehrlite	45.5	45	9.5
Olivine augitite, more than 12.5 percent olivine	45.5	44	10.5
Olivine augitite, less than 12.5 percent olivine	45.5	41.5	13
Gabbro	44.5	40.5	15
Gabbroic granulite	39	33	28

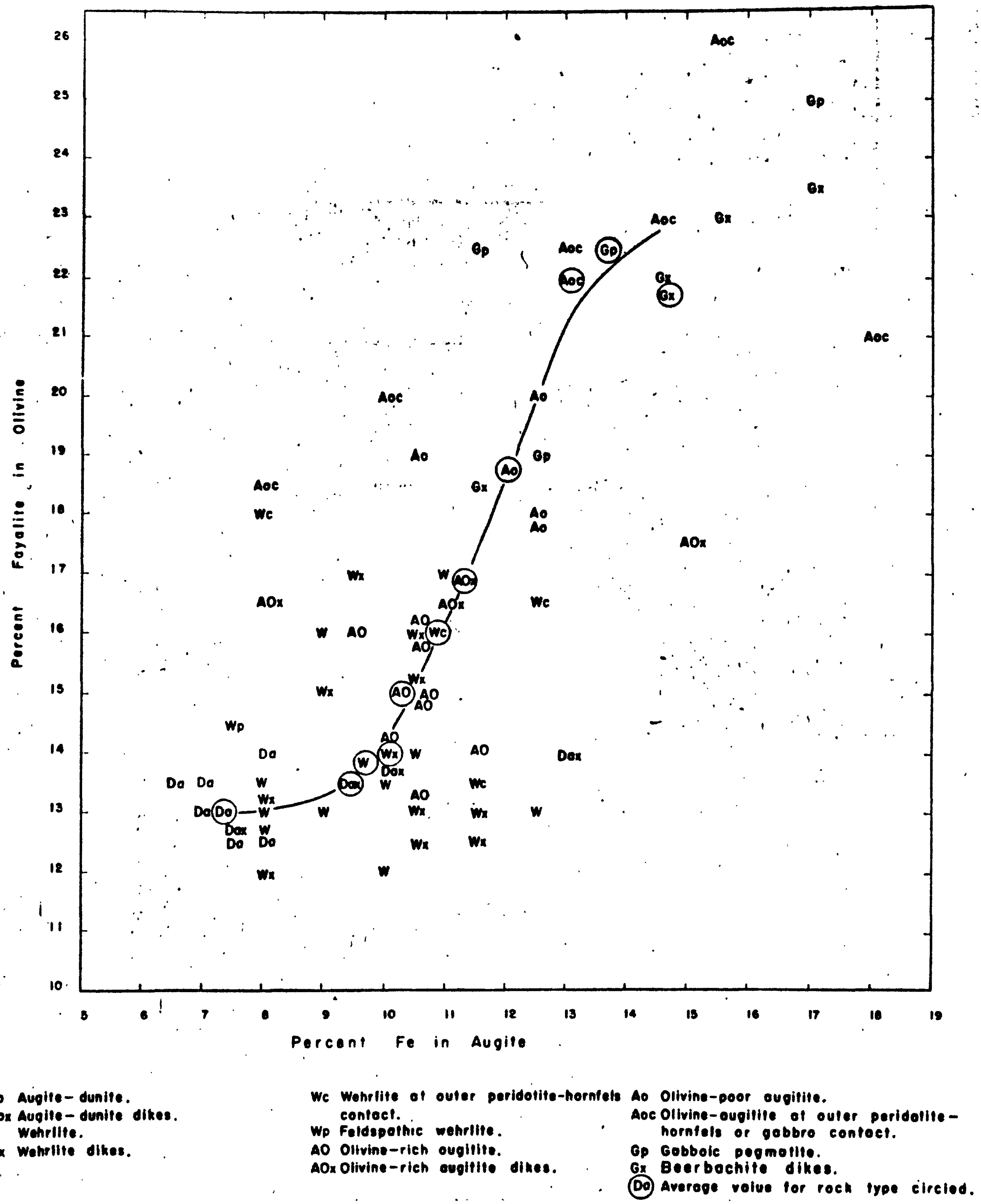

Figure 11, Relationship of fayalite content of olivine to iron content of augite in Blashke Island peridotite.

Figure 9 contains, in addition to curve A showing the trend of variation in augite in the Blashke Island rocks, a second curve, B, taken from Hess (1949, pp. 621-666) showing the trend of variation in pyroxenes from common mafic magmas. The mafic magmas indicated by Hess are gabbroic. The trend shown in the Blashke Island augites is strikingly parallel but consistently about 5 percent higher in calcium content, perhaps indicating a fundamental difference in magmas or processes of differentiation.

Figure 11 showsthe relationship between the composition of augite and the composition of the olivine with which it is associated. The paragenetic relations of olivine and augite have already been summarized. Figure 11 shows that there is a tendency for the iron content of augite to increase rapidly with respect to the increase in iron content of olivine where olivine is the major phase. Where augite is the major phase the olivine shows the more rapid increase in iron.

Hornblende is present both as a deuteric replacement of augite and as a primary phase. It is a minor late primary phase in peridotite and an important primary phase in some gabbro. The composition of hornblende is difficult to estimate even with approximate accuracy from optical properties. However optical measurements tend to show that hornblende replacing augite and primary hornblende are essentially the same, and also indicate that there is at least a slight increase in the iron content of hornblende paralleling the shift in composition of olivine and augite. The hornblende is a common hornblende and apparently contains appreciable amounts of both trivalent iron and alumina.

Plagioclase is present very sporadically as a minor, late, interstitial accessory in some olivine augitite near the outer margin of the olivine augitite ring. It is the major phase in most of the gabbroic pegmatite, beerbachite, and granulitized country rock. The plagioclase in olivine augitite and in gabbroic pegmatite in olivine augitite is anorthite containing less than 10 percent albite. Olivine augitite is in contact at its outer margins mainly with gabbro, but locally with granulitized country rocks. The plagioclase in gabbro close to the olivine augitite contact is also anorthite, but in the gabbroic granulite near contacts with peridotite it is a calcic bytownite. With increasing distance outward from contact with the olivine augitite ring, the anorthite content of plagioclase decreases both in gabbro and in granulite. At the outer contacts of the gabbro ring of the complex the country rocks are also granulitized, but less intensely than at contacts with peridotite. The granulite in contact with gabbro contains a plagioclase about as calcic as the associated gabbro, and the anorthite content falls with distance from the complex. The country rocks unaffected by contact with the complex contain abundant albite and also orthoclase feldspar. Beerbachite dikes and inclusions within the major rock units of the complex contain plagioclase ranging up to the anorthite content of the enclosing rock, but tend to contain a somewhat less calcic plagioclase. These relationships are summarized in figure 12, page 70.

Some data is presented in subsequent sections to show that other minerals such as hypersthene, biotite, and garnet, playing a less important role in the Blashke Island complex and its accompanying aureole of contact metamorphism, undergo analagous compositional variations to the variations in the major phases. Furthermore, new phases such as orthoclase and quartz are added to the complex in an order paralleling the enrichment of the major phases in their less refractory components from the interior of the complex outward.

Olivine

Olivine is almost ubiquitous in the ultrabasic rocks of the Blashke Island complex and plays an important role in all the major rock types. A substantial proportion of the olivine originally present in much of the rock is altered to serpentine. This alteration may be complete, leaving only serpentine pseudomorphs of olivine, or almost absent, but commonly alteration has taken place along fractures in the olivine, leaving angular to subangular shards of completely fresh olivine enclosed in a network of serpentine.

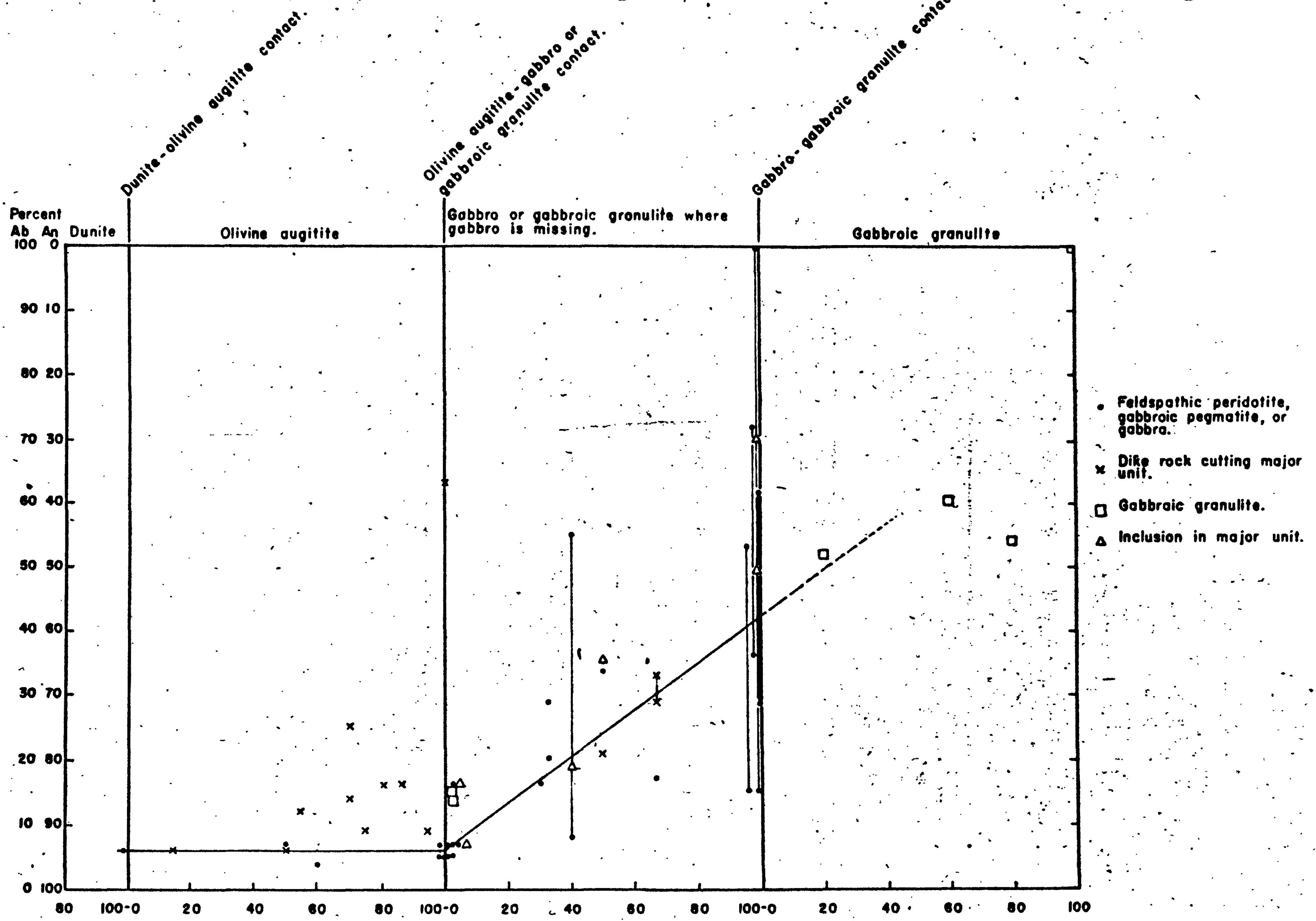

Figure 12, Composition of plagioclase in Blashke Island rocks plotted against estimated relative position in respect to major rock units of complex. Distance from the major contacts to the localities represented by the plotted points is expressed as a percentage of the estimated total thickness of the major unit. Points joined by vertical lines represent range of composition in zoned plagioclase.

Olivine is a simple orthosilicate in which magnesium and bivalent iron may substitute freely for each other. Other elements such as manganese, nickel, and titanium may be present in minor amounts. The optical properties of olivine vary with the relative proportions of magnesium and iron, particularly the indices of refraction. Graphs correlating the optical properties with chemical composition have been published by Winchell (1933, p. 191) and Bowen and Schairer (1935, p. 197). Later work by Wager and Deer (1939a, pp. 18-25) has confirmed the accuracy of these curves within most of the range of composition encountered in the Blashke Island complex. The composition is given in the above references and in this paper in terms of relative molecular percentages of the pure magnesian end member, forsterite, Mg_2SiO_4, abbreviated Fo, and the pure iron end member fayalite, Fe_2SiO_4, abbreviated Fa. The effects of possible minor amounts of other elements is not considered, but these are normally not present in significant amounts in olivine from common peridotites.

The composition of olivine was determined by refractive index measurements of olivine in 99 specimens of rock representing all observed facies of the olivine-bearing rocks in the Blashke Island complex. The intermediate refractive index, Ny, was measured and the composition determined by reference to the curves published by Winchell. These data are given in column 2 of table 1. Twenty of these refractive index measurements were made by the double variation method with an accuracy of about ± 0.0001. The remaining measurements were made with a carefully calibrated set of index oils with intervals of 0.002. The index measurements made by double variation methods were repeated with these oils and reproduced to the third decimal place, so it is believed that the accuracy of the common immersion method employed is about ± 0.001, where plenty of clean material could be obtained from the rock, but when only a small amount of partly serpentinized olivine could be obtained as in some of the gabbro and olivine-poor augitite the accuracy of measurement may be no better than ± 0.002 to ± 0.003.

The intermediate refractive indices measured for olivine from peridotitic rocks range from 1.672 in olivine from dunite near the center of the complex to 1.705 in olivine from a feldspathic olivine-augitite at the outer margin of the peridotite complex. These indices correspond to a range in composition of 90 percent forsterite - 10 percent fayalite (hereafter given, Fo90Fa10) to Fo74Fa26. The intermediate refractive indices for olivine in the gabbro and gabbroic granulites range from 1.702 in gabbro in contact with olivine augitite to 1.755 in gabbroic granulite. This corresponds to a range of Fo75.5Fa24.5 to Fo51Fa49 in the composition of olivine.

Table 3, page 61, accompanying the summary that preceded this section, shows that the composition of the olivine bears a systematic relationship to the rock type in which it appears, increasing percentages of augite being correlated with increasing iron content in the olivine, and the appearance of feldspar as a phase correlated with relatively iron-rich olivine. This relationship is brought out further by figure 7, page 62, which shows the percentage of olivine and serpentine derived from olivine plotted against the composition of the olivine for all rocks for which these data have been obtained. The presence and absence of other phases in association with olivine is also noted along the margin of the graph.

Figure 7 shows that from a fayalite content of 10 percent to a fayalite content of 12 percent, chromite is the only primary mineral besides olivine in the rock. The chromite is in small, well-formed octahedrons and commonly enclosed in olivine as shown in the photomicrograph, plate 23B. Chromite is not present as idiomorphic crystals in rocks containing olivine more iron-rich than Fa14. At a fayalite content of 11.5 percent spongy secondary magnetite appears, commonly in thin sheets in the medial planes of serpentine veinlets. Although traces of augite are present in some specimens with a minimum fayalite content, it is commonly lacking up to a fayalite content of 12 percent. From Fa12 on augite is present in all specimens, and Fa12 may be said to be the olivine composition at which this phase becomes an essential component of the rock. At Fa13 traces of oriented exsolution lamellas of an iron ore mineral are found in olivine. At Fa13.5 one thin section contained a single coarse interstitial grain of enstatite partially replaced by augite. The peridotite containing enstatite is in contact with an augite-plagioclase-enstatite hornfels, and enstatite or hypersthene is characteristic of the surrounding hornfelses, so that this occurrence may be ascribed to reaction with adjacent country rocks. Fa14 marks the upper limit of iron content in olivine associated with idiomorphic chromite. At Fa14.5 traces of plagioclase appear very sporadically. At Fa16 olivine crystals are found enclosing rounded grains of augite, and at Fa18 olivine ceases to be found as inclusions in augite. At Fa20 traces of sulfides are present in specimens within a few feet of the outer contacts of the peridotite with gabbro and hornfelsed country rocks. Olivine has a fayalite content of Fa22 or above in all rocks in which plagioclase is a major phase and is commonly later than at least a part of the feldspar because rounded grains of feldspar are not scarce as inclusions in olivine as shown by plates 24A and 24B. Olivine in gabbroic granulite is strikingly poikilitic and later than plagioclase, augite, and hornblende as shown in plates 21B and 23A.

While the composition of the olivine is related to the presence and abundance of other phases, it is also related in at least a crudely systematic way to the configuration of the complex. This is implicit in the previously described concentric arrangement of rock types which is the salient feature of the complex. Figure 8, page 63, brings this relationship in the peridotitic part of the complex into sharper focus. In figure 8 the composition of the olivine is plotted as a function of position in the complex with respect to the major contact between the dunitic and the pyroxenitic rocks. This contact was chosen as the locus of reference because it is the major structural element of the complex that is most accurately known and that best expresses the concentric structure of the complex. So far as can be determined this contact is very steep except for minor irregularities. Distance inward from the contact is plotted as a percentage of the total distance to a point chosen as near as possible to the geometrical center of the dunite core. Distance outward is plotted as a percentage of the total thickness of the outer olivine augitite ring at the point where the specimen was obtained. Normal peridotites are distinguished from peridotite dikes, from beerbachite dikes and feldspathic segregations, and from abnormal contact facies by separate symbols. Distances from the dunite-augitite contact are expressed as percentages of the exposed radius of the dunite or the exposed width of the augitite to eliminate to some extent the effects of irregularities in the exposed thicknesses of these units which may be the result of non-uniform dips in the contacts or of actual variations in thickness. In other words, the position of the olivine in the complex is given a value relative to the total thickness of the unit in which it occurs, thus a specimen from the outermost borders of the augitite ring is given the same relative position, in this case 100 percent, whether the pyroxenite is 2,000 feet in exposed thickness as it is in the southeastern part of the complex, or 500 feet thick as it is in parts of the western edge of the complex. However, if the same data are plotted in terms of absolute distances from the dunite augitite contact, essentially the same relationships are revealed with about the same dispersion of values.

Figure 8 shows that the rate of change in the iron content of the olivine is at a maximum near the dunite augitite contact, considering only the olivine in the normal peridotite facies. Inward and outward from the immediate vicinity of the contact this rate of change is more constant except for a suggestion of an increasing rate near the outer margin of the augitite. The grouping of values is fairly good within the dunite and near the contact, but the dispersion of points becomes quite large near the outer part of the augitite ring. The curve that has been sketched by inspection to bring out this relationship indicates the approximate upper limit in fayalite content reached by olivine in normal olivine augitite. Most values falling far above or below this curve are for olivine in various dike rocks and contact facies. The dispersion of the data is too great to give this curve more than illustrative significance, but it does show that the contact between rocks consisting largely of olivine to rocks consisting largely of augite is marked by an abrupt increase in the iron content of the olivine. Reference to the composition of olivine in gabbro and gabbroic granulite in tables 1 and 3 show that there is a further abrupt increase in iron content in passing from augitite to gabbro and from gabbro to gabbroic granulite. Although the change in composition of olivine is more abrupt at the contacts between major rock units, there is a distinct gradation in composition within each unit.

The data indicate that the olivine in equilibrium at the dunite-augitite contact has a composition of Fo87Fa13 to Fo86Fa14, and in fact there are no normal massive peridotites containing olivine more magnesian than Fo85Fa15 outward from this contact. On the other hand the data show that dike rocks of olivine-rich peridotite tend to have an olivine with a composition near that of the average composition of olivine at the contact, and lower in iron than the olivine in the augite-rich rocks in which they are emplaced. In contrast the beerbachite dikes and feldspathic segregations tend to have a higher iron olivine than the enclosing rocks and near the maximum in iron content for olivine in the complex. This relationship suggests that the beerbachites and feldspathic segregations are truly late differentiates or products of country rock assimilation, while the augite-dunite and wehrlite dikes and outlying tabular bodies that are emplaced in the olivine augitite are intrusions derived from the periphery of the inner dunite core.

Further references will be found to the mineralogical and petrological relationships of olivine in connection with the discussion of augite beginning on page 78 , orthopyroxene beginning on page 87 , and plagioclase beginning on page 97 . Olivine in some of the feldspar and hornblende-bearing rocks is rimmed by coronas of pale green amphibole, pale green amphibole and magnetite, or hypersthene and pale green amphibole. Other corona-bearing minerals are also present in some rocks, and coronas will be taken up in a separate section beginning on page 134.

Throughout the complex the olivine is clear and colorless in thin section with normal birefringence and dispersion. Average dispersion for 20 magnesian olivines measured by the double variation method is $Ny_F - Ny_C = 0.0132$. The olivine is invariably fractured in the characteristic curving, disoriented network pattern. Replacement by serpentine is commonly present along these fractures in olivine in the peridotitic rocks but much of the iron-rich olivine in the beerbachite, gabbro and gabbroic granulite is very little serpentinized. The boundary between serpentine and olivine is commonly smooth and sharp and the walls of the fractures are sensibly parallel even though the original fractures have been widened by replacing serpentine to such an extent that the volume of serpentine in the rock is commonly greater than the volume of unaltered olivine in the peridotites. Replacement by serpentine may, however, etch the walls of the fractures in a sawtoothed or scalloped fashion.

In addition to the curving fractures, much of the olivine seen in thin section has distinct but imperfect cleavage parallel to (010), and some sections show relatively rare, very straight, hair-line cleavage traces parallel to (001). Serpentinization does not follow these cleavages to a noticeable extent.

Many sections of olivine also show strongly oriented inclusions or intergrowths in the form of thin lamellas in the (100) plane. These inclusions are of two kinds; very thin, opaque graphic intergrowths of ore, possibly magnetite or ilmenite, and even thinner rectangular plates of a deep brown, isotropic mineral, that may in fact be an ore mineral in such thin plates that it is translucent. The thickness of these lamellas is on the order of 0.01 mm or less. In the (100) plane, that is to say, in plan, the opaque intergrowths form intricate, lobate figures reminiscent of Chinese or Hebrew written characters. This graphic character is caused by a tendency for the opaque mineral to grow in narrow lobes elongated parallel to the b-axis and to the trace of the (021) plane, while perpendicular to the plane of growth, that is, parallel to the a-axis there is virtually no growth. A band of graphic intergrowths of this type is shown crossing an olivine grain in plate 25A. The translucent brown lamellas are sharply rectangular in outline parallel to the b and c-axes and distinctly elongated parallel to b. They also show a faint streakiness in color parallel to b. No traces of these intergrowths were found in olivine with an iron content lower than Fa13. They are common in olivine richer in iron in the peridotite, but not in the gabbro and gabbroic granulite. In some sections the olivine in a narrow zone surrounding these intergrowths exhibits lower birefringence. The olivine shows no evidence of open fractures or any sort of latent cleavage or weakness in the plane of the intergrowths. The intergrowths are clearly primary and not introduced. They antedate serpentinization, shown by the fact that delicate lamellas pass through veins of serpentine from one fresh fragment of an olivine crystal to another with uninterrupted pattern and continuity.

Lamellar inclusions of ore with similar orientation have been reported by Wager and Deer(1939, p. 21) in the Skaergaard complex in olivine ranging in fayalite content from Fa59 to Fa97. They were not present in olivine of Fa36. Wagner (1929, pp. 55-59) reports the same phenomena in an Fa48 hortonolite from the Bushveld Complex. In both instances they were described as inclusions, suggesting that they had formed prior to or contemporaneously with the crystallization of the olivine. The delicate nature of these lamellas, their control by crystallographic directions in the olivine, and the lesser birefringence noted in some grains in a zone around the intergrowths indicate that they are the result of exsolution of an iron ore mineral.

Two microscopic features of the olivine are of great structural significance in the peridotites. Although practically all grains of olivine are shattered into numerous shards and partially replaced along the fractures by serpentine, the several fragments of each olivine grain commonly preserve a perfectly uniform optical orientation, proving that the fracturing and serpentinization of the olivine was neither accompanied nor followed by very appreciable flowage or deformation in either a solid or semi-solid state. This conclusion is further strengthened by the fact that the very delicate graphic intergrowths described above may be observed in many instances passing from one fragment of fresh olivine to another through a vein of serpentine with no evidence of displacement or distortion.

Serpentinization appears to have been an entirely static process of volume for volume replacement entirely subsequent to emplacement of the rock. The volume changes, if any, attendant upon serpentinization must have been taken up by the utilization of the space within the rock occupied by interstitial fluids used up in the process of serpentinization. In view of the granular character of the rock and the crackled habit of olivine this source of space may suffice for whatever volume change that took place.

Augite

Megascopically the augite varies from light, clear green to dark bottle green. It is colorless and non-pleochroic in thin section in all of the peridotitic rocks, but has a faint blue-green tint in the beerbachite, gabbro, and gabbroic granulites. An iron-rich augite in granulite (specimen 368, item 164, section 22, table 1) is pale lavender-pink in color and has distinct dispersion $r > v$ of optic axes B with week dispersion of optic axis A. Dispersion is weak on optic axis B and not discernable on axis A in the augite of the peridotite and gabbro, and birefringence is not extreme or anomalous. Diallage parting is present locally and in some slides augite both with and without evidence of diallage parting is present without any apparent difference in other properties.

Hess has recently published charts correlating the optical properties of common clinopyroxenes with their chemical compositions (Hess, 1949, pp. 621-666). Professor Hess very kindly supplied the author with preliminary copies of his charts long in advance of publication and they have been used to investigate the variations in composition of the augite throughout the complex. The composition of common augite varies principally by the substitution of magnesium, calcium, and bivalent iron for each other and is expressed by Hess in terms of the relative atomic percentages of these three elements. This is somewhat different than the common procedure of giving the composition of clinopyroxene in terms of calculated end members: clinoenstatite, wollastonite, and ferrosilite, or diopside and hedenbergite. However, the basic information conveyed by the two methods of representation is the same. This procedure neglects the effect on optical properties of other elements usually present in pyroxene to a small extent, mainly sodium, manganese, nickel, aluminum, trivalent iron, chromium, and titanium. Hess states that trivalent iron in appreciable quantities gives augite distinct greenish tints, while titanium produces purplish tints. The substitution of aluminum for silicon reduces the birefringence. The augite of the Blashke Island peridotites is colorless and has normal birefringence, but the augite in the gabbro and gabbroic granulite is faintly colored and probably contains appreciable trivalent iron and titanium. Sodium is conspicuously low in the plagioclase associated with the complex. On the other hand, chromite is a common accessory in the olivine-rich portion of the complex, and chromium may be present in the augite of the peridotites. Hess states that chromium enters into the clinopyroxenes of igneous rocks in the amount of 1.1 percent with 7.0 percent Fe, and falls to nearly zero at 13 percent Fe. This is the range of composition in which much of the Blashke Island augite tends to fall. Special provision is made in his charts for the effect of chromium in this range of composition. Therefore it seems valid to assume that the determination of the composition of augite from its optical properties by the use of Hess' curves will give close approximations of the true composition with the addition of up to about 1 percent chromium. The validity of this assumption is confirmed by the analyses of olivine augitite and wehrlite which are in good agreement with the chemical compositions calculated from the modes based on optical determinations of the composition of the augite.

The intermediate refractive index (Ny) was determined for the augite in 105 specimens of rock representing all the principal rock types within the complex. These determinations were made with calibrated oils at 0.002 intervals and are believed accurate to about ± 0.001.

2V was measured with a universal stage on 67 specimens. Only sections of augite in which the acute bisectrix was nearly vertical and both optic axes could be brought into the axis of the microscope were used. The refractive indices of the pyroxene ranges from 1.679 to 1.697 with most values falling near 1.686. Hemispheres of refractive index 1.649 were used on the universal stage. No measurements were made requiring inclinations of more than 38 degrees, so that corrections for refraction between hemispheres and mineral were not large, usually less than 1 degree. Values that departed appreciably from the normal values for other specimens with the same refractive indices were checked again and were generally found to coincide with the first determination within ± 1/2 degree so that the dispersion of values found in 2V is believed to be, in part at least, due to variations in composition of the pyroxene.

The optical data and the composition of augite derived from the data are given in column 3 of table 1 for all specimens measured.

The composition as determined from Hess' curves by refractive index and optic angle measurements is plotted in figure 9, page 65, for all specimens for which both properties were measured in the Blashke Island complex. Figure 9 corresponds in arrangement to plate 1 on page 634 of Hess' paper referred to above. A second figure has been prepared on a much larger scale (fig. 10, p.66) showing only the section of the diagram in figure 9 in which most of the values fall. On the second diagram the points are denoted by symbols that indicate the rock type in which the augite occurred. These points establish a fairly well-defined trend in the composition of augite throughout the complex. This trend has been indicated by curve A which has been drawn through the points by inspection. The trend as indicated by curve A shows very little variation in the calcium content except in the iron-rich augite of the gabbroic granulite. The principal trend is in the ratio of iron to magnesium and falls near the diopside-hedenbergite line. An unusual dike rock cutting olivine-augitite, specimen 390, item 103, table 1, previously described on page 40 , consists of augite and secondary andradite garnet. This augite had the lowest refractive index of any measured. The composition of the augite in this rock is indicated by the symbol Aax in figure 10. The symbol Da? indicates the composition of augite as determined in a specimen of augite-dunite containing only 4.6 percent of augite (specimen 179, item 26, table 1). The augite in this rock had the lowest refractive index of any measured in the normal peridotites of the complex, but unfortunately only one rather poorly oriented grain could be found in thin section from which to measure 2V so that this value is in doubt. Specimens Aax and Da?, both with low refractive indices, have relatively high values for 2V and suggest a trend toward the composition of pure diopside rather than a continuation of the trend indicated by curve A toward a calcic endiopside at the low iron end of the series. However the probable nonmagmatic origin of specimen 390 has been pointed out on page 41 .

In addition to curve A indicating the course of variation in composition of the Blashke Island pyroxenes, a second curve (B) has been added to figure 9 . This curve is the curve given by Hess for the normal trend of crystallization of clinopyroxenes from common mafic magmas. Curves A and B are nearly parallel, but curve A indicates that the augites from the Blashke Island peridotite systematically contain about 5 percent more calcium and 5 percent less magnesium than the augites from normal mafic magmas, which brings them nearer the diopside-hedenbergite line. An inspection of the analyses given by Hess shows that the augites which fall along the normal curve given by him, that is, the augites with 40 percent more or less of calcium, are mainly derived from gabbro, norite, diabase, and related rocks. On the other hand, the analyses of more calsic augites cited by Hess are from a variety of rocks, including websterite, bronzitite, anorthosite, syenite, and skarn. This suggests that the normal trend in change of composition during crystallization of augite in basaltic magmas is distinctly different from the normal trends under a variety of other conditions. The displacement of the trend of crystallization in the augite of the Blashke Island peridotite from the trend shown by basaltic magmas may be one indication that the petrogenetic processes or the magmas involved have fundamental differences even though some of the end products such as the gabbroic rocks are petrographically similar.

The trend in composition of the augite in the Blashke Island complex is correlated both with the trend toward increasing iron content in the olivine from the core of the complex outward and with relative abundance of augite in the rock. Figure 11 shows the percentage of iron in augite plotted against the fayalite content of olivine in all rocks in which both have been determined in the peridotite part of the complex. Where only the refractive index of augite was measured the composition has been determined by the intersection of the refractive index curves given by Hess with curve A of figure 9. The correlation is far from perfect but nevertheless distinct. The various rock types and modes of occurrence represented by the specimens are denoted by separate symbols. A tendency toward grouping of like rock types together is noticeable in the normal peridotites, while the feldspathic peridotites, dike rocks and contact facies of the peridotites are more wide-ranging. Inspection of the data in table 1 shows that the composition of the augite is correlated with distance inward and outward from the main dunite augitite contact to a lesser degree than olivine. It tends to fall within a certain range for each rock type without much relationship to the distance from the contact, except to the extent that the rock types themselves have a concentric arrangement.

A curve has been drawn through the points representing the average values for the iron content of olivine and augite of the various rock types shown in figure 11. Although the individual values plotted on this chart show considerable dispersion, the average values fall close to a smooth curve. It is probable that observational errors somewhat accentuate the dispersion of the individual points and that the averages are more representative of the true trend than the relative degree of dispersion would suggest. Furthermore the dispersion of values is greater in the dike rocks and contact facies than in the normal peridotites. This curve is interesting in that it has a sharp change in slope in the region where olivine has a fayalite content of about 13.5 percent. This is the average value for the fayalite content of olivine at the contact between the olivine-rich and the augite-rich rocks. It indicates that within the olivine-rich rocks the composition of the augite changes steeply with respect to the composition of the olivine, while in the augite-rich rocks it is the olivine that undergoes the greater composition change. There is also a suggestion in the data that as olivine approaches its maximum iron content in the outer contact facies and gabbroic differentiates the composition of the augite undergoes a more rapid trend toward a higher iron content. These relationships point toward the idea that the contacts between the major rock types in the complex and the concentric arrangement of rock types result from shifting chemical equilibria rather than that they result from entirely mechanical processes of intrusion or differentiation.

The correlation of iron content in olivine and pyroxene in the complex is continued in the gabbro and gabbroic granulite, data for which are not shown on figure 11 owing to the extreme values for iron content in olivine and augite in some of these rocks. Olivine in the gabbro ranges up to Fa29.5 associated with an augite containing 16.5 percent Fe, and in the granulite an olivine with 49 percent fayalite is associated with an augite containing 27.5 percent Fe. However the highest iron augite found in the complex is in the olivine-free nodular inclusion in specimen 280, item 159, table 1, with an iron content of 37 percent. The matrix in which this nodule is embedded contains a very high iron olivine (Fa47), but the augite in the matrix carries only 18.5 percent Fe. Biotite is present in the matrix and not in the nodule. If the nodule were originally a calcareous fossil, concretion, pebble, or amygdule, this relationship may indicate that a high-iron olivine formed in the matrix because of a deficiency in calcium and that where calcium was in high concentration all available iron was used up in augite without the formation of a non-calcic phase, particularly if the matrix were originally argillaceous so that extra alumina was present to combine with available calcium to form plagioclase.

Augite is not found or is present only in minute traces in the central dunite core of the complex. Within a few hundred feet of the main contact between the olivine-rich rocks and the pyroxene-rich rocks, streaks and patches appear in the dunite containing a few percent of augite. From the point where pyroxene first appears near the margins of the dunite it tends to increase in abundance outward, but the increase is not everywhere uniform, giving the marginal areas of the dunite a streaky to mottled aspect. The contacts between the pyroxene-bearing marginal facies of the dunite core and the pyroxene-rich rock is generally relatively sharp; in some places it may be an actual surface of discontinuity with olivine-augite on one side and augite-dunite or wehrlite on the other, it may be the locus of some shearing and minor displacement, or in other places it is sharply gradational with pyroxene increasing from a minor to a major percentage of the rock within a few inches or feet. An altogether smoothly gradational increase in pyroxene is not characteristic.

Some contacts between olivine-rich rock and pyroxene-rich rock give the impression that there has been an intimate interdiking and admixture of the two rocks along the contact. Tongues of augite-dunite or wehrlite a few inches wide pass out into the olivine augitite and gradually become wispy and indistinct through an admixture of pyroxene until they disappear. Stringers of rock containing a relative abundance of pyroxene form apophyses into the augite-dunite or wehrlite and gradually fade into the enclosing rock by diminishing pyroxene content. Some of these bodies seem to be merely streamers of loosely aggregated pyroxene crystals rather than discrete apophyses. Inclusions of coarse to fine granular pyroxene are common in the contact facies of the dunite. These inclusions range in size from small, rounded clots of pyroxene crystals a few inches in section to large rounded masses 10 to 15 feet in section. In texture and composition they range from granular, fine-grained masses of pure augite to olivine-rich pyroxenites with coarse-grained, almost euhedral augite and interstitial olivine. Dike-like bodies of coarse pyroxene are common in the contact facies of the dunite and consist of disoriented augite crystals, commonly as large in cross section as the width of the dike. A pyroxene rich, granular wehrlite, richer in olivine than the typical olivine-augitite and poorer in olivine than the typical wehrlite and augite-dunite of the contact facies of the dunite, is locally present in indistinct masses along the contact, sending apophyses out into both major rock units so that the same body cuts across the contact to form an olivine-rich dike in the pyroxenitic rock and a pyroxene-rich dike in the olivine rock. These bodies are small and their limits and forms are indistinct and gradational.

Where pyroxene first appears in the marginal areas of the dunite its relationship to the olivine is completely interstitial. This interstitial relationship is characteristic in all the rocks classed as augite dunite. In dunite the olivine forms a mosaic of more or less equant grains which tend to show some faint semblances of crystal form in spite of mutual interference. Where pyroxene is present, the tendency of olivine to display crystal forms is accentuated, and the pyroxene occupies interstices between somewhat blocky olivine grains. Areas of pyroxene representing a single crystal may be extremely irregular in form with larger areas connected by narrow necks and outlying areas unconnected in the plane of section. This texture represents an early stage in the development of a coarse poikilitic aggregate consisting of pyroxene poikilocrysts enclosing olivine as shown in plate 16A, page 246 .

With a larger percentage of pyroxene, typified by the wehrlite group, coarse crystals of pyroxene enclosing olivine are characteristic. Single crystals of pyroxene more than a centimeter in cross section are not uncommon, and these may enclose ten or twenty grains of olivine. The olivine grains enclosed in the augite commonly exhibit distinct crystal forms, but with an increasing amount of pyroxene the enclosed olivine grains tend to become rounded.

Where augite is the predominant mineral, olivine shows no traces of crystal form but tends to be deeply embayed and irregular in form, occupying irregular spaces between augite grains that locally have a blocky habit with suggestions of crystal form against olivine. These textural relations suggest that augite is a late primary, interstitial phase against which olivine is stable in the rocks in which pyroxene is present in small amount, but that where pyroxene is the dominant phase it replaces early-formed olivine, leaving only irregular remnants of olivine. As has been pointed out above, this difference in relationships with larger amounts of augite is accompanied by a change in the composition of olivine toward a more iron-rich phase.

Considerable evidence is seen in thin section to suggest that above a certain range of iron content in olivine the order of crystallization between olivine and pyroxene is reversed. Augite is observed enclosing grains of olivine up to Fa18 in iron content, rarely higher; while olivine is commonly found enclosing augite grains from an iron content of Fa16 and higher. Photomicrographs of augite and hornblende pseudomorphs after augite enclosed in olivine are shown in plates 17A and 17B, page 247. Inclusions observed in thin section may be projections into the apparently enclosing grain from above or below the plane of section, but augite inclusions in olivine have been observed in seven thin sections of peridotitic rock and in a number of gabbro and beerbachite slides. Therefore the commonly observed interstitial relationship of olivine to pyroxene in the olivine augitites, described above, may be in part at least due to the later crystallization of olivine. However, there appears to be no doubt that much olivine is interstitial to pyroxene due to having crystallized early and having been replaced by augite. This is certainly true of all olivine with a fayalite content of less than 16 percent.

Alteration of augite to hornblende is common but not extensive. Alteration tends to be more advanced in the rocks in which augite is most abundant. Many slides of augite-dunite and wehrlite show little, if any, secondary hornblende. The augite is either quite fresh, or dusty with opaque inclusions. However, in most augite-rich rocks the augite is shot through with little scraps and shreds of secondary hornblende in parallel orientation with the augite up to 10 to 15 percent of the total augite originally present. Serpentinization has had little effect on the augite; in most specimens, none. A few slides show thin veins of serpentine cutting the augite, but scarcely enough to make an appreciable percentage of the rock. Here and there in a few slides a fracture or cleavage crack in augite is filled with a deep amber-brown alteration product resembling bastite, but the amount of this mineral is negligible.

Orthopyroxene

Orthopyroxene is all but absent within the peridotitic portion of the Blashke Island complex. In the hornfelsed sediments surrounding the complex and in what appears to be a highly contaminated facies of the gabbro forming the outer ring of the complex it is a characteristic phase. A few grains were found in a specimen of feldspathic wehrlite from a point on the southwestern border of the complex where peridotitic rocks are in sharp contact with hornfelses. No grains could be isolated for a determination of refractive index, but the mineral is optically positive with large axial angle and faint pinkish pleochroism, indicating that it is enstatite near the upper limit in iron content. A small cluster of strongly pinkish, optically negative hypersthene grains associated with secondary magnetite is present in a thin section of a plagioclase-augite-hornblende granulite dike cutting olivine-augitite near its contact with the outer ring of gabbro. This small cluster of hypersthene grains and magnetite appears foreign to the rest of the rock and may represent an inclusion derived from without the complex. An inclusions of hornfelsed sediments displaying relict bedding found within coarse olivine augitite near its outer contact with gabbro and sediments contains abundant hypersthene with an intermediate refractive index of 1.687, indicating a composition of $En_{81}Fs_{19}$ (Winchell, 1933, p. 218 and Kennedy, 1947, p. 564). It seems clear that orthopyroxene is present in the peridotite rocks of the complex only where there has been contamination by contact with the enclosing sediments.

Orthopyroxene also plays a very minor role as one of the minerals found in some coronas around olivine. The subject of coronas and their constituent minerals will be taken up separately on pages 134-8.

Traces to fractions of a percent of hypersthene have been found in many specimens of olivine gabbro as shown by the modes in section 16 of table 1. Much of this hypersthene is present only in coronas around olivine, but a few primary accessory grains are present in some specimens. However, hypersthene can scarcely be regarded as an essential component of the gabbro. The gabbroic rocks that do contain substantial percentages of hypersthene are very dubiously assigned to the gabbro on the basis of a conventional interpretation of field relations. Modes and mineralogical data on two rocks of this kind are given: specimens 356 and 230, items 140 and 141, section 21, table 1. Specimen 356 is from a narrow, irregular dikelet with coarse texture that appears to be an apophysis into hornfelsed country rock from a small body of coarse gabbro with irregular texture near contact with peridotite on the west side of the complex. It contains 29.0 percent hypersthene and 12.7 percent quartz. Although the texture is coarse, under the microscope it has a distinct crystalloblastic-granular aspect, and despite the seeming intrusive relations of this rock it seems far more likely that it represents a vein formed by recrystallization along a fracture in strongly heated country rock aided by fluids given off by the ultrabasic mass, than that it represents a peculiar magmatic differentiate. Specimen 230 is similarly suspect. It was collected at a contact between gabbro and country rock on the northeast side of the complex where irregular masses of hornfelsed country rock seem to be caught up in a network of streaky, indistinct masses of coarse, uneven textured gabbroic rock. The contacts between blocks of hornfels that clearly show their origin by relict bedding and granulitic texture and coarse, gabbroic rock are vague and gradational. The hornfels seem to pass into coarse hypersthene gabbro by a gradual change in the proportions and grain size of the constituent minerals. The same phases are present in both. Here again the presence of hypersthene seems to be symptomatic of conversion of gabbroic granulite into coarse gabbro by a process of progressive recrystallisation, possibly brought on by partial fusion or solution along systems of fractures aided by fluids from the ultrabasic mass.

Hypersthene is common in the gabbroic granulites where it ranges in composition from En78Fs22 to En64Fs36. Apparently a distinction can be made between gabbroic granulites containing olivine and those containing hypersthene. The granulites that contain olivine generally contain only traces of hypersthene, and those that contain hypersthene generally do not contain olivine. Both olivine and hypersthene are generally associated with a deep reddish-brown biotite. The hypersthene-biotite association apparently represents a somewhat lower grade of metamorphism than the olivine-biotite association, because the hypersthene-biotite rocks pass more abruptly into less altered hornfelses. The presence of hypersthene without biotite, however, does not seem to follow this rule because specimen 363, item 157, section 22, table 1, comes from direct contact with peridotite and consists essentially of augite, hypersthene, and plagioclase, while specimen 368 in the same section of table 1 was collected about 30 feet from the same contact and contains olivine and biotite. Original composition of the hornfelsed rock certainly controls the appearance of both hypersthene and olivine to a considerable extent because simple augite-plagioclase granulites are of equal rank and intimately associated with rocks containing olivine and hypersthene. The presence of olivine in the matrix but not in the pebbles of a hornfelsed conglomerate suggests that hypersthene as well as olivine develop only in rocks that were originally somewhat argillaceous. The presence of additional alumina may have used up calcium to form calcic plagioclase, leaving an excess of iron and magnesium that would otherwise have combined with calcium in augite. Locally coarse gabbroic granulite with irregular texture and streaks approaching gabbro in appearance contains coarse nodules and streaks of mafic minerals. Specimen 266, item 153, table 1, is representative of one of these mafic nodules. It contains 64.2 percent coarse hypersthene with abundant augite, some hornblende and accessory plagioclase. From the standpoint of mineral assemblage it is a websterite, but it is found in a nodule in gabbroic granulite only a few inches in cross section.

The hypersthene in all the rocks in which it is found is generally somewhat more altered than either the augite or the olivine, if present, in the rock. However, all the minerals in the granulites are generally relatively fresh because the dense texture of the rock makes it relatively impervious to attack by fluids. Biotite as well as talc and bastite have been noted as alteration products.

Hornblende

Hornblende is present in the Blashke Island peridotites both as a late primary phase and as a secondary alteration product of pyroxene. It is present, but rarely, as a primary mineral in wehrlite and olivine augitite and abundantly in the beerbachite dikes. A few specimens of wehrlite and olivine augitite contain scattered coarse grains of primary hornblende, entirely interstitial to olivine and interstitial to and partly replacing augite. In the beerbachite dikes hornblende is one of the major constituents. It tends to become more abundant as the feldspar becomes less calcic, olivine disappears, and augite becomes richer in iron. Some of the beerbachite dikes are so rich in hornblende that they can be styled hornblendite.

Hornblende is one of the major constituents of the gabbro. Olivine gabbro and augite-rich gabbro generally contain only coarse, ragged anhedra of hornblende enclosing all the other silicates poikilitically. Toward the outer margins of the gabbro ring a part of the hornblende appears to have crystallized simultaneously with the augite and part of the plagioclase, while some is pseudomorphous after augite and some is later than the other principal silicates.

Hornblende is a principal constituent of inclusions of country rock caught up in the gabbro and olivine augitite. Some of the inclusions are virtually hornblendite in composition. In general the inclusions in gabbro have been metamorphosed to a more mafic rock than the host. They commonly contain a larger total percentage of augite and hornblende than the host gabbro, and a larger percentage of each of these minerals than the host, but some inclusions show a lesser degree of replacement of augite by hornblende than does the host gabbro and the inclusions thereby have a lower percentage of hornblende than the host, though exceeding the host in total mafites.

Contact metamorphosed country rock external to the complex does not contain hornblende in close proximity to contacts with the complex except along fractures and shear zones where some late secondary hornblende is locally present. The only hydrous mineral present in the higher ranks of gabbroic granulite is biotite. A few hundred feet from contacts with the complex hornblende appears along with biotite in coarse porphyroblasts. In the country rocks unaffected by contact metamorphism a pale green, fibrous amphibole is very common and some of the rocks approach amphibolite in composition.

Secondary hornblende is present wherever pyroxene is abundant. It is found in irregular shreds and scraps within grains of augite in the same crystallographic orientation as the pyroxene forming the familiar uralitic alteration of pyroxene. The extent of uralitic alteration tends to be greater toward the outer contacts of the peridotite complex. The augite in augite dunite commonly shows only the slightest indication of uralitic hornblende. It is generally present only in traces in wehrlite and makes an appreciable percentage of the rock in only a few specimens of olivine augitite. Some gabbro has all but the slightest traces of its original augite replaced by hornblende. The properties of the secondary hornblende in thin section are the same as the properties of late primary hornblende found in the same rocks.

Table 5
Optical data for hornblende

Item no., Table 1	Specimen no.	2V	Z angle ȼ	Ny	Pleochroic in shades of:	Rock type in which found
45	133B	+82	19	1.652	pale pink to pale green	wehrlite
58	0132	90	19.5			wehrlite dike
62	202	-L		1.655	pale green	olivine augitite inclusion in wehrlite
63	369	90	20	1.651	pale green	olivine augitite
70	98	-84	20		pale green	olivine augitite
99	335			1.650	very pale yellow	alteration of anorthite in gabbroic pegmatite
99	335			1.656	pale green	primary hornblende in gabbroic pegmatite
101	233			1.659	greenish yellow to green	gabbroic pegmatite
104	333	-88	20	1.658	greenish yellow to green	olivine beerbachite
105	334			1.657	greenish yellow to green	olivine beerbachite
106	367			1.660	greenish yellow to green	olivine beerbachite
107	137			1.659	brown	olivine beerbachite
109	283	-84	18.5	1.657	yellow-green	beerbachite
110	205			1.675	dark brownish green	beerbachite
111	141	-88	20	1.657	yellow-green	beerbachite
112	99	-84	18	1.656	yellow-green	beerbachite
113				1.657	yellow-green	beerbachite
114	207			1.657	yellow-green	beerbachite
116	278	-M	15	1.641	very pale yellow	outlying dike of augitite
120	220	-64	19.6			gabbro
143	284			1.658	yellow to green	inclusion in olivine augitite
144	138			1.659	yellow to green	inclusion in olivine augitite
168	232			1.656	green	country rock over 400 feet from complex

L = large, M = moderate.

The optical properties of hornblende that have been measured are given in table 5. Refractive indices were measured by ordinary immersion methods. 2V and Z angle ¢ were measured on the universal stage. The intermediate refractive indices range from 1.651 to 1.657 in the peridotitic rocks, 2V ranges from 82°(+) to 84°(-), Z angle ¢ from 19° to 21.5°. Winchell (1945, pp. 27-51) and Sundius (1946) have sought to correlate the optical properties with the chemical compositions of the amphiboles. The complexity of the amphibole group makes it difficult to do this with any great precision. However, it appears from the data given by Winchell that the hornblende in the Blashke Island rocks cannot be referred to the tremolite-actinolite series. The data of both Sundius and Winchell indicate that these hornblendes are decidedly aluminous with small to moderate amounts of ferrous and ferric iron. The optically positive hornblende is probably close to pargasite, and the hornblende with 2V near 90° or negative is probably somewhat richer in iron.

In the beerbachite dikes and in inclusions in peridotite the intermediate refractive index ranges from 1.656 to 1.660, 2V from 88°(-) to 84°(-), and Z angle ¢ from 18° to 20°. These hornblendes therefore are probably just a little richer in iron than those in the peridotites. The hornblende in gabbro corresponds in range of properties to that in the beerbachite dikes and the inclusions, except that some hornblende in gabbro is pleochroic in strong brownish-green to brown.

A few small dikes cutting olivine augitite have a coarse, pegmatitic texture with elongated crystals of hornblende up to several inches in length growing inward from the walls toward the center forming the so-called comb structure. Specimen 205, item 110, table 1, is representative of these dikes and contains a hornblende with Ny = 1.675 and pleochroic in shades of very dark brownish green. This hornblende is probably much richer in iron than that common in the complex.

Several rocks contain an amphibole belonging to the tremolite-actinolite series. In some of the basic pegmatite segregations and dikes calcic plagioclase is partially replaced by a very pale green actinolite. An outlying dike of pyroxenitic composition, specimen 278, item 116, table 1, contains a ferriferous tremolite with Ny = 1.641, Z angle ¢ = 15°, and a moderate negative optic angle. X is colorless and Y and Z are very pale yellow.

An unusual variety of hornblende is present in several specimens of wehrlite and olivine augitite as a late primary phase partially replacing augite (photomicrograph, plate 18A and specimens 133B, 361, and 362; items 45, 89, and 88; table 2). This hornblende is in large, clear grains, some of which are distinctly pleochroic in pink or reddish-brown and others in pale, clear green. A few grains shade from pink pleochroic colors to green with complete optical and crystallographic continuity. The pinkish pleochroism is exactly like that observed in hypersthene and where the hornblende cleavage angle is not apparent the mineral may easily be taken for hypersthene. The optical properties are Ny = 1.651, 2V = 82°(+), Z angle ¢ = 19°. It is probably near pargasite in composition.

The appearance of an aluminous hornblende as a primary phase late in the crystallization of the ultrabasic rocks of the complex and as a secondary alteration product parallels the appearance of plagioclase feldspar and indicates that a very small amount of alumina present in the original magma or derived by contamination from aluminous country rocks was concentrated in the late-crystallizing fraction and mainly in the outer margins of the peridotite. The trend of the probable tenor of iron in the hornblende also parallels the trend in iron content in the olivine and augite toward the outer part of the complex and in the late-crystallizing dikes and segregations.

Biotite

Biotite is of negligible importance in the peridotitic rocks of the complex. Some of the gabbroic pegmatite bodies in the olivine augitite contain a little biotite, and some of the beerbachite dikes cutting olivine augitite have traces of biotite. Biotite is present only in traces also in the gabbro, the largest modal percentage found being 1.4 percent in specimen 14, item 135, table 1, from an extreme marginal facies of the gabbro. Biotite in the gabbro tends to be altered to a bleached, pale, yellowish-brown mineral.

Biotite is one of the principal phases of moderately high rank to medium rank gabbroic granulites. In the higher ranking granulites it is commonly associated with an iron-rich olivine or with hypersthene, and in these rocks it is the only hydrous phase present. Biotite is abundant in granulites of moderate rank either as the principal dark mineral or associated with a green hornblende.

The biotite in the rocks of the complex is pleochroic in reddish-brown and is somewhat stronger colored in the gabbroic granulites than in the gabbros or gabbroic pegmatites. Biotite from a gabbroic pegmatite in the olivine augitite ring of the complex, specimen 233, item 101, table 1, had an intermediate refractive index of 1.612. Biotite from two specimens of granulite, one of moderately high rank containing olivine, specimen 280, item 159, table 1, from the near vicinity of a contact with peridotite, and the other, specimen 232, item 169, table 1, from a quartz-hornblende-adularia granulite about 400 feet from contact with gabbro, had intermediate refractive indices of about 1.635. According to the optical data published by Winchell (1933, p. 274) these biotites would lie toward the magnesian side of the series from potassium-magnesium to potassium-iron biotite with the biotite in the granulite 15 to 20 percent higher in iron than the biotite in the gabbroic pegmatite.

Garnet

Garnet was found in the ultrabasic part of the complex in one unusual dike rock, specimen 390, item 103, table 2, previously described on page 40. The dike rock consists essentially of moderately coarse diopsidic augite and small-grained granular garnet in rounded grains without crystal form. The garnet is disposed through the rock in clusters around the margins of augite grains and enclosed in augite (photomicrograph, plate 20B). It appears to have formed partly as a replacement of augite.

Both the garnet and the augite are almost colorless in thin section and hand specimen and the rock is almost white with a faint greenish tint in hand specimen. Except for the heft it might be taken in the field for an aplite. The refractive index of the garnet is considerably above 1.84, the highest immersion medium available to the author. An X-ray powder pattern gave all the characteristic lines of garnet. The unit cell dimension, $a_0 = 12.00 \pm 0.01$. According to Stockwell (1927, pp. 327-344) this corresponds to an almost pure andradite, $Ca_3Fe_2Si_3O_{12}$, containing about 5 to 8 percent of other garnet components. An analysis of the rock is given under column M of table 2. The rock has the highest calcium content of any analyzed rock in the complex; and the iron content compares with the other peridotites.

The olivine augitite in contact with the dike contains no garnet and shows no sign of alteration except for microscopic sheeted fractures paralleling the dike contact. The dike itself has a very fine-grained granular texture in a zone along the contact and here contains a little plagioclase feldspar. It also contains some inclusions of serpentine that appear to be pseudomorphic after augite. Toward the center, the dike becomes coarser grained. The origin of the garnet appears to be related to the crystallizing of the dike and not to externally induced alteration.

Another occurrence of garnet was noted in a felsitic rock, probably originally an andesitic lava flow, specimen 500, item 164, table 1, that has undergone mild contact metamorphism at a distance of about 500 feet from an outlying mass of gabbro and about 1,700 feet from the main mass of the complex on the west side of the complex. The rock contains numerous nodular light greenish-gray masses with coarser texture from a fraction of an inch to an inch and one half in cross section. These masses are probably relicts of amygdules filled with zeolites or carbonates, although they may be of some other origin. They contain a colorless garnet with a refractive index of 1.77 along with augite, zoisite, and plagioclase. It is probably a garnet in the grossularite-andradite series relatively near grossularite in composition.

A narrow irregular dike with coarse gabbroic texture cutting a hornfels inclusion in gabbro consists of calcic plagioclase, augite and large grains of a dark cinnamon brown garnet that is deep golden yellow in thin section. The refractive index of the garnet is well above 1.83. This dike is a couple of inches wide and has the relations of an apophysis from the gabbro enclosing the hornfels, but the garnet suggests that the dike is at least in part derived from reactions between country rock and fluids from the enclosing gabbro.

Plagioclase feldspar

Plagioclase is present in the peridotitic rocks of the Blashke Island complex only as a sparsely and irregularly distributed minor phase, but is, of course, a major constituent of all the other rocks of the complex. At only one place in the complex does a rock approaching dunite in composition contain any plagioclase. This area at the northern end of the large elongate island within the central lagoon of the Blashke Islands contains a few square yards of exposures of wehrlite, approaching augite-dunite in composition, in which a little interstitial plagioclase is sparsely disseminated. Specimen 247, item 43, table 1, is from this locality. Near the outer parts of the olivine augitite ring small patches of rock containing streaks or isolated interstitial grains of plagioclase are not uncommon. Specimens 215, 216, 122, and 364, items 81, 83, 92, and 93, table 1, are representative of this facies of the olivine augitite. At one place on the western border of the complex an unusual facies of the complex consisting of a feldspathic wehrlite containing 12.6 percent of an unidentified alteration product derived from plagioclase is in contact with country rocks (specimen 362, item 88, table 1). In all of these peridotitic rocks the plagioclase is extremely calcic. Determinations of composition by refractive index measurements, extinction angles, and the universal stage range from Ab_4An_{96} to Ab_7An_{93}. The plagioclase in these rocks is not zoned.

The olivine augitite member of the complex also contains sporadically distributed, small, irregular masses and dike-like bodies of coarse feldspathic rock with a pegmatitic texture as described on page 41 and pictured in plates 7, 8, and 9. These pegmatitic rocks contain coarse, unzoned anorthite grains up to an inch in cross section and their range of composition is the same as that of the disseminated anorthite in the peridotite. Specimens 335, 244, and 233, items 99, 100, and 101, table 1, are from ultrabasic pegmatites. Plate 24B is a photomicrograph of coarse olivine, Fo77.5Fa22.5, enclosing anorthite, Ab4An96, and plate 25B shows olivine of the same composition enclosed in anorthite of the same composition in the same specimen (no. 244, item 99). There is no trace of reaction between the two minerals.

Plagioclase is one of the essential minerals of the beerbachite dikes that are found cutting the olivine augitite and in these rocks it ranges in composition from Ab6An94 to Ab25An75. In olivine gabbro very near the contact with the peridotitic core of the complex the composition of the plagioclase is approximately the same as that found within the peridotite, but away from the contact with peridotite the albite content of the plagioclase tends to increase systematically with distance from the peridotite both by an increase in the minimum albite content of the inner zones of plagioclase and by a greater tendency toward zoning with more sodic outer shells. Finally near the outer margins of the thicker parts of the gabbro ring a little pure albite appears in outermost zones as shown by specimen 101, item 134, table 1, from the gabbroic portion of an intrusion breccia at the outer gabbro contact. The same fairly systematic shift toward a higher albite content with distance away from the complex is shown by the plagioclase in the gabbroic granulites. Albite is common in the country rocks unaffected by contact with the complex.

Data on the composition of plagioclase is given for all rock specimens in which it was measured in table 1. Figure 12 is a schematic graphical representation of the relationship of the composition of plagioclase to the configuration of the complex, and shows the trend toward higher sodium content with distance from the peridotite. Within the peridotite the composition of the plagioclase is virtually constant except for the beerbachite dikes of gabbroic composition. A line has been drawn on the chart by inspection to show the approximate trend in composition of plagioclase in the major rock units of the complex, beerbachite dikes and inclusions excluded.

Plagioclase is later than augite in all rocks in which augite is the most abundant phase, but earlier than augite where augite is subordinate. Poikilitic plagioclase enclosing augite may be observed in augite-rich rocks and poikilitic augite enclosing plagioclase in augite-poor rocks. An example of coarse poikilitic plagioclase is seen in plate 27A. Plagioclase is later than olivine where the olivine contains less than about 20 percent fayalite, but highly calcic plagioclase in contact with more iron-rich olivine has the same ambiguous relations observed between iron-rich olivine and augite. Both olivine and plagioclase are observed enclosing each other in the same specimens as shown in plates 24B and 26B. Coronas between olivine and plagioclase are found in some beerbachites and olivine-gabbros, but not in others, and the discussion of coronas will be reserved for a later section, pages 134-8.

Megascopically all of the plagioclase is chalk-white in color. Under the microscope it is colorless and commonly perfectly clear. Twinning is varied. Manebach, pericline, parallel and complex twinning have been identified with the universal stage. Albite twinning is the most common, but all the other kinds of twinning combined are probably as frequent as albite twinning. Twin lamellas tend to be very coarse. The highly calcic plagioclase is virtually unzoned but zoning is pronounced in the intermediate calcic plagioclase in gabbro. Zoning is absent in the plagioclase in gabbroic granulite.

In some rocks plagioclase has undergone alteration to a completely isotropic mineral without distinctive structure, form, or cleavage. In oil immersions the grains of this material are ragged and weakly translucent as though it were an amorphous aggregate. Its refractive index appears to range from about 1.58 to 1.66. It has not been identified, but it may be colloidal alumina hydrate. Another common alteration product is leucoxene in an opaque to brownish cryptocrystalline aggregate that is white in reflected light and in hand specimen. Leucoxene is commonly associated with the unidentified isotropic substance. In the gabbroic rocks plagioclase is commonly fresh, but locally saussuritized. Alteration to prehnite and heulandite has also been noted. Plagioclase is commonly unaltered in the granulites.

Orthoclase feldspar

Orthoclase is extremely scarce in the Blashke Island complex. In one specimen of the outermost facies of the gabbro, 3.8 percent interstitial sanidine was found. This rock (specimen 4, item 135, table 1) was collected at the outer margin of the gabbro ring at its widest point in the northeast sector of the complex. The rock, as shown by the mode and mineralogical data given in table 1, is actually a hornblende diorite with accessory quartz and sanidine, but it grades through continuous exposures into typical gabbro as represented by specimen 15, item 128, table 1, collected about 500 feet inward toward the center of the gabbro in the same general sector of the gabbro as specimen 14. The rock has typical coarse gabbroic texture and the sanidine along with quartz occupies angular interstices between the other primary minerals. The sanidine is clear and colorless, small 2V (-), and optic plane parallel with 010.

In the gabbroic granulite an orthoclase feldspar is generally not found near the contacts with the ultrabasic complex, but in specimen 280, item 159, table 1, 4.3 percent of granular orthoclase was found along with a moderately calcic plagioclase, Ab50An50, olivine, Fo53Fa47, biotite, and augite. A fault separates this rock from the nearest outcrops of peridotite, but it was probably within a hundred feet of contact with peridotite during its metamorphism. Specimen 232, item 169, table 1, collected 400 feet from the nearest gabbro or peridotite contact contains granular orthoclase as its most abundant feldspar. Orthoclase feldspar is a common mineral in the low-grade greenstones unaffected by contact with the ultrabasic complex.

Quartz

Quartz is a most uncommon mineral in the Blashke Island complex. Within the peridotite only one quartz-bearing rock was found, specimen 261 (vein), item 117, table 1. This rock is found in a few thin vein or dike-like bodies occupying a set of almost horizontal joints cutting olivine augitite very close to its contact with gabbroic granulite at the northern edge of the complex. The rock is coarse grained and pure white in color and consists of andesine with some interstitial quartz and a very minor percentage of accessories. An analysis is given in column Q of table 2.

A little interstitial quartz is present in specimen 14, item 135, table 2, previously described on page 100. This rock is a facies of the gabbro found at the outermost edge of the widest part of the gabbro ring. Another facies of the gabbro, specimen 356, item 140, table 1, contains 12.7 percent interstitial quartz associated with augite, hypersthene, and labradorite-bytownite plagioclase. The rock is found in a narrow vein cutting gabbroic granulite. As has been suggested previously on page 50, the magmatic origin of this rock is dubious.

Quartz is not present in the higher rank contact metamorphosed gabbroic granulites. Where the intensity of metamorphism drops off within a hundred or a few hundred feet of the complex, quartz is present in the rocks, and quartz is common in many facies of the country rocks unaffected by contact with the ultrabasic complex.

Sphene

Sphene is a noticeable accessory mineral only in the gabbro where it commonly occurs in small to comparatively coarse allotriomorphic grains. Sphene probably accounts for an appreciable share of the TiO_2 shown in the gabbro analysis, column U, table 2, but in the other rocks of the complex the TiO_2 must be largely present in ilmenite, titaniferous magnetite, or leucoxene.

Apatite

Apatite is virtually absent in the peridotitic rocks of the Blashke Island complex. The analyses given in table 2 show only traces of P_2O_5 in dunite and augite dunite and 0.01 percent in the other peridotites. The gabbroic pegmatite found within the olivine augitite contains moderately abundant accessory apatite (P_2O_5 = 0.16 percent), the gabbro contains apatite as a relatively abundant accessory, locally over 2 percent of the rock. The analysis of a composite specimen of gabbroic granulite given in column Y, table 2, gives 0.31 percent P_2O_5. In the gabbro and gabbroic pegmatite, apatite is in typically minute prisms, but in the gabbroic granulite it is in the form of scattered irregular grains, generally elongated parallel to ϕ, and as coarse as the other constituents of the rock. The apatite in the granulite is distinctly biaxial with an estimated 2V of 10° to 15°, negative.

Chromite

Chromite is a sparse but ubiquitous accessory throughout the dunite and augite dunite in very small, well-formed octahedral crystals. It is much less abundant in recognizable crystals in wehrlite and present in olivine augitite only as very minute inclusions in olivine. The chemical analysis of the olivine augitite and wehrlite give approximately the same content of Cr_2O_3 as do the analyses of dunite and augite dunite. The Cr_2O_3 in these rocks is either combined in pyroxene or in chromite with the same allotriomorphic habit as magnetite and thus not identified. Chromite is completely opaque in sections of normal thickness, but very small fragments are clear reddish-brown. In reflected light the crystals are jet black with an iridescent tarnish (photomicrograph, plate 23B). The chromite is nonferromagnetic to the extent of giving no response to contact with a powerful alnico permanent magnet. An X-ray powder pattern made from a crystal isolated from the dunite (specimen 316, item 6, table 1) gave the unit cell dimensions, $a_0 = 8.33 \pm 0.01$. Clark and Ally (1932, pp. 66-74) have given data correlating the lattice dimensions of chromite with its alumina content. According to their curves the chromite from the Blashke Islands corresponds closely to the composition of pure chromite, $FeCr_2O_4$, and contains less than 5 percent Al_2O_3. It is probably low in ferric iron as indicated by its lack of ferromagnetism and by the fact that the X-ray powder pattern made with copper radiation and a nickel filter showed very little fogging from scattered radiation. The chromite may be high in Mg substituting for Fe^{++}.

Chromite is apparently the earliest mineral to form in dunite and augite dunite. The crystals are idiomorphic against all other phases. Some crystals are crackled in a manner similar to the olivine but to a much lesser degree, and the cracks are filled by serpentine. One or two examples of zoning in chromite were observed with grains containing transluscent red-brown cores passing into opaque rims. A few crystals have been observed with sharp crystal outlines but with a few small, vein-like apophyses projecting out from the grain, apparently representing secondary magnetite growing outward from the grain during serpentinization. A few chromite grains were observed with distinct rims of oriented serpentine surrounding them, as shown in plate 23B. The serpentine in the rims differs slightly in color, pleochroism, and apparent birefringence from the mass of surrounding serpentine and is crystallographically oriented with X normal to the chromite crystal faces. However the chromite grains show little indication of replacement by serpentine or of other alteration.

Chromite forms practically all of the opaque material in dunite, but with the appearance of the augite phase in appreciable amount, veinlets of secondary magnetite accompanying serpentinization become abundant. Chromite appears to be scattered at random through the dunite. No concentrations of chromite of the slightest economic interest were noted. The average modal content of chromite in dunite is 1.3 percent, in augite-dunite 0.7 percent, and in the other rocks it is present only in traces as recognizable crystals. The Cr_2O_3 content of the non-peridotitic rocks is much less than the peridotites or nil.

Magnetite and ilmenite

Magnetite is one of the minor late primary constituents, but it is present in the rocks of the complex principally as a by-product of serpentinization. Its occurrence in this way has been described under serpentine, page 113 . It is also probably the opaque mineral in the graphic exsolution lamellas described under olivine. Some magnetite is present in the beerbachite dikes, gabbro, and gabbroic granulites where it appears in formless grains partially replacing silicates and later than the silicates.

The average magnetite content of the peridotites ranges from practically nil in dunite to 3.8 percent in wehrlite dikes and 3.7 percent in wehrlitic rocks at the outer contacts of the complex. However locally in a few places magnetite is a major constituent of the rock, forming a mesostasis for olivine and augite in rocks of wehrlitic character. This texture has been described by Duparc (Duparc and Grosset, 1916, pp. 59-62) who styled it, "sideronitique," and gave the name "koswite" to peridotitic rocks exhibiting this texture and composed of diallage, olivine, and a little hornblende. Specimen 410, item 95, table 1, is representative of koswite (photomicrograph, plate 26A). It contains 25.9 volume percent of magnetite which is massive, not spongy, and interstitial to the silicates. A little pyrite is present with the magnetite. Koswite is very sporadically distributed and does not make up an important percentage of the exposed rocks of the complex. Koswite is mainly found locally near the contact between dunite and olivine augitite and appears to be gradational with wehrlite and olivine augitite containing normal amounts of magnetite. Apparently there were local concentrations at a late stage of an iron-rich residue, because serpentinization could not have produced such an abundance of magnetite. Except for proximity to the dunite-olivine augitite contact, no special structural control of the occurrence of these rocks could be observed in the field.

The chemical analyses in table 2 and the variation diagram for minor constituents of the complex, figure 16, page 152, show that titanium is several times more abundant in the gabbroic rocks than in the peridotites, and it is possible that ilmenite is an accessory in these rocks, though none has been isolated for positive identification.

Pseudobrookite (?)

A thin section of gabbroic granulite, specimen 285, item 160, table 1, contains 0.3 percent of very small well-formed crystals of a mineral tentatively identified from the thin section as pseudobrookite. The crystals are strongly colored and pleochroic, Z = deep reddish-brown, X = greenish-brown. Relief is very high and birefringence is high. The mineral is optically positive. Some crystals are simple twins, apparently twinned on a prism face. The mineral is an accessory in a contact metamorphosed rock in which the major constituents are: plagioclase, hyperstnene, augite, biotite, apatite, and sulfides. Pseudobrookite is reported from a number of localities as a minor constituent of contact metamorphosed basalts and in xenoliths in volcanic rocks, in some localities associated mineralogically with hypersthene (Palache, Berman and Frondel, 1944, pp. 736-738).

Sulfides

Sulfides play a subordinate role in the Blashke Island complex. Sulfides are present locally in sparsely disseminated interstitial grains in outer marginal facies of the olivine augitite. Some of the gabbroic pegmatite within the olivine augitite contains interstitial masses of coarsely crystalline pyrite. The gabbro ring of the complex contains scattered masses of rock where disseminated sulfides make up several percent of the rock. Disseminated sulfides in scattered granules are common in the gabbroic granulites. No veins containing concentrations of sulfide minerals are associated with the complex, although joints in the gabbro and gabbroic granulite locally contain tissue-thin blebs of sulfide minerals.

Pyrite is the dominant sulfide in the complex, but traces of pyrrhotite, pentlandite, chalcopyrite, and bornite have been noted. Two assays of Blashke Island gabbro containing several percent of sulfides have been reported by Kennedy and Waltoh (1946, p. 78), and two assays and spectrographic examinations of sulfide-bearing gabbroic granulite were made for this report by the United States Bureau of Mines, Stephen M. Shelton, assayer. The results of these analyses are tabulated below.

Table 6

Results of assays on sulfide-bearing rocks of the Blashke Island complex.

	Percent					Oz. per ton
	S	As	Cu	Co	Ni	Pt group
Gabbro, 43AK295	NR	NR	0.0086	NR	0.03	0.1
Gabbro, 43AK306	NR	NR	0.016	NR	0.05	0.1
Gabbroic granulite, 464WtF	1.6	ND	0.001 to 0.01	0.01 to 0.1	0.01 to 0.1	ND-FA
Gabbroic granulite, 464WtF	2.5	ND	0.001 to 0.01	0.01 to 0.1	0.01 to 0.1	ND-FA

NR = not reported, ND = not detected, ND-FA = not detected by fire assay.

Another assay of a specimen of gabbro reported by Kennedy and Walton in the report cited above showed 0.004 oz. of gold, 0.04 oz. of palladium, and a trace of platinum per ton. It is clear from the above assay reports that pyrite is the principal sulfide in the Blashke Island rocks, and that the mineral association of pyrrhotite, pentlandite, and chalcopyrite so commonly found throughout the world associated with rocks derived from gabbroic magmas is of minor importance in the Blashke Island complex.

Serpentine

All of the rocks in the Blashke Island complex that contain olivine also contain serpentine that formed by the replacement of olivine. Commonly the percentage of serpentine present is greater than the percentage of unaltered olivine remaining. The percentage of olivine serpentinized varies from about 90 percent to about 35 percent in dunite, augite dunite, and wehrlite. In olivine augitite and in some of the contact facies of wehrlite the percentage of olivine serpentinized has a wider range and the olivine is almost completely fresh in some specimens. In the beerbachite dikes, the gabbro, and the gabbroic granulite, the olivine is commonly almost completely fresh, but locally altered to strongly colored serpentine with much secondary magnetite.

A number of names have been applied to different species and varieties of serpentine. The usage is far from uniform in the literature. Most authorities (Winchell (1933) pp. 260-261 and 280-281, Rogers and Kerr (1942) pp. 360-363, Lodachnikov (1936) pp. 4-5) recognize two principal species, chrysotile and antigorite, distinguished on the basis of optical properties and habit. Varietal names such as serpophite, asbestos and bastite are based on habit or mode of origin. Selfridge (1936, pp. 489-490), Gruner (1939, p. 186), and Aruja (1945, pp. 65-74) have shown that there are probably two distinct dimorphous structures with the formula $(OH)_8Mg_6Si_4O_{10}$ corresponding to the minerals chrysotile and antigorite. However, Selfridge concluded that both minerals can occur in massive, lamellar, and fibrous forms, and that there is no reliable optical method of distinguishing between the two dimorphs.

Caillère (1936, pp. 163-326) concluded from a very detailed physical, optical, chemical, thermal, and X-ray study of numerous varieties of serpentine (many of them type specimens of such varieties as antigorite, metaxite, picrolite, schweitzerite, dermatine, picrosmine, bowenite, williamsite, dewylite, and chrysotile) that there were no valid physical, optical, or chemical differences between these substances. Differences that are observed, such as optic sign, were shown to be due to differences in mode of aggregation of the same minutely fibrous mineral. Caillère did, however, show that these minerals could be divided into two groups on the basis of thermal behavior which she called alpha and beta antigorite. Her X-ray studies by means of powder patterns revealed only slight, and to her negligible, differences between these two groups. Caillère proposed that all serpentine minerals be called antigorite with the alpha and beta varieties distinguished on the basis of thermal properties, and serpentine be used as a rock name for rocks composed of any variety of antigorite.

The distinguishing thermal behavior of alpha and beta antigorite as defined by Caillère is that alpha antigorite undergoes an endothermic decomposition at about 650°C., followed by a sharp exothermic reaction between 750°C. and 825°C. due to recrystallization. Beta antigorite undergoes an endothermic reaction at about 650°C. but gives no immediately following exothermic reaction, and this is explained by Caillère by recrystallization concomitantly with the breakdown of antigorite masking the exothermic effect by the endothermic effect. Caillère noted that alpha antigorite was characteristic of surficially altered or hydrothermally altered serpentine that generally showed a deficiency of combined water and an excess of adsorbed water, while the beta variety was generally confined to fresh serpentine that had not been affected by weathering or hydrothermal attack.

Although Caillère described no significant differences in the X-ray powder patterns of the numerous varieties of serpentine she investigated, Selfridge, Gruner, and Aruja concluded that there are two serpentine dimorphs. Aruja's study, which is the more recent and is based on oscillation and Laue photographs as well as powder photographs, yielded the tentative conclusion that both forms have a structure consisting of a polar arrangement of kaolin-like sheets of atomic layers of the following sequence: $O_6\text{-}Si_4\text{-}O_4(OH)_2\text{-}Mg_6\text{-}(OH)_8$, but that a limited degree of imperfection is present in the antigorite lattice. These studies indicate that all of the so-called minerals of the serpentine group are variants due to mode of aggregation and crystal habit of either the same mineral or two closely related dimorphs with the same composition. The many names that have been in vogue for types of serpentine may perhaps be retained as varietal names for descriptive purposes, but are not valid mineralogically. Selfridge found that specimens of serpentine that had been identified as belonging to the same "species" gave different powder patterns, while many different "species" gave the same powder pattern. Caillère found a similar condition of utter confusion in the thermal behavior of "species" as based on physical and optical properties. Since a detailed X-ray study of the serpentine in the Blashke Islands has not been attempted, no attempt will be made to distinguish between antigorite and chrysotile or to apply the usual varietal nomenclature. All of the material will be referred to as serpentine following the practice recommended by Gruner (1937, p. 102). However, practically all of the serpentine in the Blashke Island rocks would be classified as antigorite and serpophite if the ordinary optical criteria were applied. A little late serpentine occupying partings in veinlets of early serpentine would be called chrysotile on the same basis, and some strongly colored material occurring as pseudomorphs of olivine fragments is probably a low-alumina chlorite.

The first stage in the process of serpentinization in the Blashke Island rocks is the development of pale, almost structureless serpentine along grain boundaries and in a dense network of fractures in the olivine. Each veinlet shows traces of a medial fracture or parting bisecting the veinlet longitudinally and may show one or two sets of parallel partings on either side of the medial parting. The crystallographic orientation of the serpentine in this initial stage of development is remarkably uniform with respect to the veinlets that it occupies. X is normal to the length of the vein and Y and Z parallel the vein, thus simple veins always have positive optical elongation. In some sections the veins may exhibit a faint ribbon structure due to a slight difference in color and pleochroism in a band along the center of the vein on either side of the medial fracture. It was shown in the discussion of olivine (p. 78) that the serpentine veinlets formed after movement had ceased in the complex and that the veins were formed by replacement of olivine. The medial parting in the serpentine veins almost certainly represents the locus of the original fracture in olivine with serpentine replacing the olivine inward from the fracture on both sides.

In cross polarized light these veins may show a faint transverse structure which is best seen when the mineral is near the extinction position. A very slight difference in extinction in very narrow bands transverse to the vein gives the appearance of a fine cross-fiber structure parallel to A. In most veins this structure is perpendicular to the vein walls and parallel to the extinction direction X, but in some sections the structure is diagonal to the trend of the vein by as much as 30°. However in these sections the extinction direction, X, remains sensibly normal to the vein, giving the structure the appearance of inclined extinction. This seeming cross-fiber structure is not the result of a fibrous crystallographic habit parallel to X, but is probably caused by shearing along the vein inducing a strain effect in the mineral. Selfridge (1936, pp. 489-490) has described analogous structures which he also attributes to the warping of the fibro-lamellar structure of the mineral.

The serpentine forming in the initial stage does not appear to be uniform in composition. It ranges in color from pale yellowish white or yellowish green to strong yellow, greenish yellow, or gray green, and the pleochroism increases with the intensity of the color. In general the stronger colored serpentine is associated with olivine having higher fayalite content. Serpentine associated with olivine containing more than 12 percent fayalite commonly appears cloudy or dusty in thin section due to minute, thinly disseminated opaque grains. This opaque material is evidently magnetite. Quantities of magnetite may be extracted by a small permanent magnet from the powdered serpentine and small grains of serpentine containing a heavy concentration of this opaque dust are attracted by the magnet. The indices of refraction of the serpentine from any given specimen show a certain range of values, but the range tends to extend to higher values in serpentine associated with iron-rich olivine. All of the serpentine that displays any degree of optical uniformity is optically negative with 2V small - approaching unixiality. Ny is approximately equal to Nz and ranges from a minimum of 1.560 in colorless, almost isotropic grains to 1.568 in pale green varieties, 1.578 in strongly green varieties, and to between 1.59 and 1.60 in grains showing amber discoloration related to weathering. An immersion of fragments of serpentine from a single rock specimen will show a variety of grains giving distinct, well-centered, acute bisectrix interference figures with a range in indices depending on the color and also on the relative opacity or cloudiness of the serpentine caused by disseminated dusty inclusions. However, serpentine from dunite with olivine not exceeding about 11.5 percent fayalite generally does not exceed 1.570 in refractive index except where discolored by weathering, while serpentine from augite dunite and wehrlite with olivine ranging up to Fa16 may have strongly colored serpentine ranging up to 1.580 in index, and higher if discolored by weathering.

Differential thermal analyses were made of two specimens of partially serpentinized peridotite. One specimen, number 315, item 6, table 1, is dunite containing 72.1 percent serpentine by volume. The serpentine is very pale green in color and non-pleochroic in thin section and is derived from olivine with a fayalite content of 10.5 percent. The other, specimen 177, item 22, table 1, is augite dunite containing 48.8 percent of serpentine that is distinctly pleochroic in thin section from yellow to green and derived from olivine with a fayalite content of 12.5 percent. The differential thermal curves are given in figure 13, page 112, along with several curves from the literature for comparison. The curves for the Blashke Island specimens are closely comparable. The difference in amplitude is doubtless due to the different percentages of serpentine in the two rocks. There is a shift of about twenty degrees downward in the temperature of the exothermal peak for the pleochroic variety, suggesting that the pleochroism is due to combined iron.

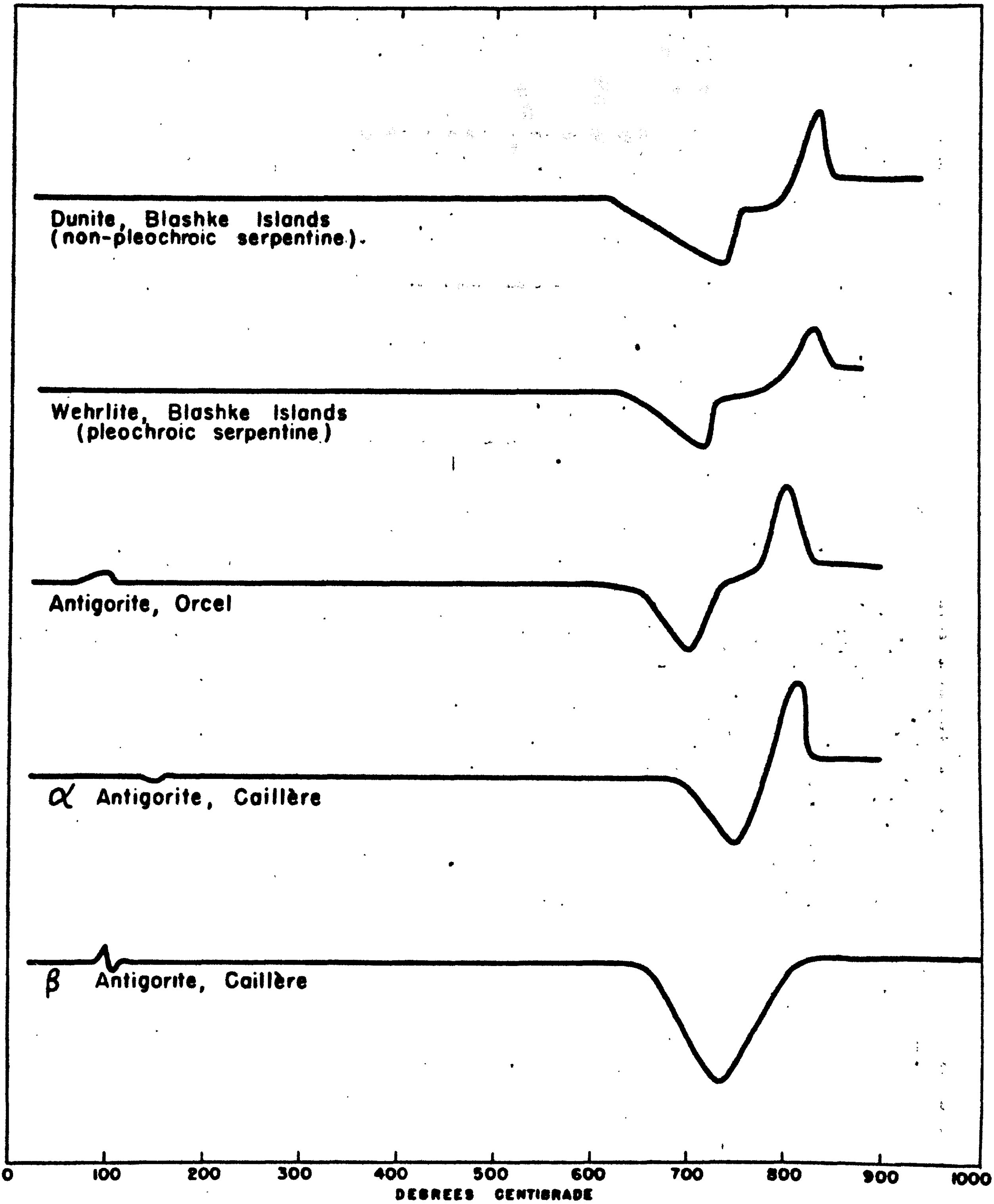

Figure 13,. Differential thermal curves for serpentinized peridotite and for antigorite.

The alpha curve by Caillère (1936, p. 215) and the curve for antigorite by Orcel (1927, p. 237) were made on specimens of the famous antigorite from Tilly Foster, New York, with cubic cleavage. The beta curve by Caillère (1936, p. 223) is on a specimen identified as chrysotile from Montville, New Jersey. The difference in the antigorite curves on the same specimens as given by Caillère and Orcel may reflect differences in apparatus. The pattern and temperatures of reaction are approximately the same as the patterns for serpentinized rock from the Blashke Islands. Little support however is seen in the Blashke Islands for Caillère's contention that the alpha curve typifies serpentine derived from surficially or hydrothermally altered serpentine. All the olivine-rich rocks in the Blashke Islands are rather uniformly serpentinized throughout with no signs of control by weathered surfaces, shear zones, or other avenues of hydrothermal attack. Talc and carbonates are present in only minute amounts, and the ratio of adsorbed to combined water is very small as shown in the chemical analyses.

The initial stage of serpentinization does not appear related in any way to the extent of weathering exhibited by the rock or to features such as joints and shear zones that control the advance of weathering and other types of external alteration, except for a reddish-brown discoloration of the serpentine concentrated along joints and shears. This discoloration appears to be produced by disseminated colloidal ferric oxide in the serpentine, and it causes a definite increase in refractive indices without any increase in pleochroism.

The second stage in the process of serpentinization is the development of very low birefringent to almost isotropic serpentine, with lower refringence than the original serpentine, along the medial partings of the previously formed veinlets. It is commonly necessary to use the sensitive violet accessory plate to detect the birefringence of this material, and its elongation with respect to the length of the vein is always negative, or opposite to the elongation of the first-formed serpentine. In rocks containing olivine with a fayalite content of 11.5 percent or more, the formation of serpentine of this second stage is accompanied by the formation of spongy magnetite, usually in the form of narrow ribbons along the medial partings within the secondary serpentine, but also in irregular masses in rocks with iron-rich olivine. This secondary serpentine appears to form at the expense of the primary serpentine and releases iron in the form of magnetite.

Concurrently with the development of low-birefringent serpentine in the centers of the veins is the sporadic local replacement of entire olivine shards by very low birefringent to isotropic serpentine. These pseudomorphs of serpentine after olivine consist of a felted mass of very thin, disoriented folia. The low birefringence may be due to the interference of diversely oriented folia. Where the material shows some degree of crystallographic uniformity the birefringence ranges up to a somewhat anomalous bluish-gray. Spongy secondary magnetite in irregular masses also accompanies the formation of this material.

Some serpentine replacing entire shards of olivine with relatively high fayalite content is strongly colored and pleochroic in shades of yellowish-green. Birefringence ranges up to first order yellow with an anomalous greenish tint. The properties are those of an alumina-poor chlorite near negative penninite. The mineral occurs in radiating clusters of thin folia, and its abundance seems to be related partly to the relative richness in iron of olivine and partly to the extent of weathering. Frasche (1941, pp. 280-305) has shown that in the development of lateritic iron ores from peridotite, the fresh peridotite consists of olivine and pyroxene veined by serpentine with abundant fresh olivine in shards surrounded by a network of serpentine. As this rock passes upward in a matter of tens of feet into lateritic iron ore, the fresh olivine shards become replaced in the initial stages by dark, greenish-black serpentine, and this stage of serpentinization is definitely related to the weathered profile of the rock.

The inhomogeneity in color, pleochroism, and refringence in the serpentine suggests that the mineral is not a simple homogeneous phase with a fixed composition. Part of the inhomogeneity may be explained by the effects of varying amounts of disseminated inclusions, but part of it must be due to variations in the composition of the serpentine itself. Winchell (1936, pp. 642-651) has published a correlation of the optical properties and chemical composition of the chlorite series in which he shows that there is a gradation in composition and properties between antigorite and the chlorites. He considers antigorite to be an end member of the chlorite group which varies in composition by the substitution of ferrous iron for magnesium and aluminum for silicon. The most abundant serpentine in dunite in the Blashke Island complex has the following properties:

Color and pleochroism — X = pale yellow, Y = Z = pale gray-green

Optic sign and angle — Negative, 2V nearly zero

Intermediate refractive index — 1.568

Birefringence — 0.007

This would correspond to antigorite with about 16 molecular percent of ferroantigorite ($(OH)_8Fe_6Si_4O_{10}$) according to Winchell's correlation. The commonest serpentine in the augite dunite and wehrlite at the dunite-augitite contact has approximately the following properties:

Color and pleochroism — X = pale greenish-yellow, Y = Z = gray-green

Optic sign and angle — Negative, 2V nearly zero

Intermediate refractive index — 1.578

Birefringence — 0.008

This corresponds to antigorite with about 23 percent ferroantigorite according to Winchell. Other serpentine found in the same rocks would range from almost pure antigorite to a chlorite with appreciable amounts of aluminum as well as iron. However, it should be noted that the iron entering serpentine according to Winchell's scheme is considered to be in the ferrous state. Winchell points out that iron in the ferric state has a stronger effect on color and refringence. Smaller quantities could thus produce comparable effects.

An examination of published analyses of serpentine and serpentinized peridotites reveals what seems to be a curious discrepancy in the ratio of ferrous to ferric iron between analyses of serpentine minerals and analyses of rocks composed in whole or in part of serpentine. Most analyses in the literature that purport to be analyses of serpentine minerals, such as antigorite or chrysotile, show Fe_2O_3 as very low or nil, if it is listed at all. On the other hand these analyses commonly show several percent of FeO and the amount of FeO ranges up to about 15 percent. For example, out of 46 analyses of serpentine minerals in the 6th edition of Dana (1892), in which both oxides are listed, only 8 show Fe_2O_3 in excess of FeO, while 31 give Fe_2O_3 as nil. It is perhaps significant, however, that 8 of the 14 analyses that give any value for Fe_2O_3 show it in excess of FeO. A survey of all the analyses given in Mineralogical Abstracts, from 1920 to date, reveals essentially the same situation in more modern analyses.

In the case of rock analyses the situation is quite the reverse. Ferric iron is far in excess of ferrous iron in typical serpentinite analyses. The percentage of combined water in analyses of peridotite is a fairly good index of the extent of serpentinization. Pure antigorite has 12.9 percent combined water and therefore as the combined water in peridotite approaches about 13 percent the rock approaches complete serpentinization. The degree of serpentinization can be indicated by expressing combined water as a percentage of the total combined water necessary for complete serpentinization. If the percentage of total iron that is in the ferric state as shown in analyses of peridotites in varying degrees of serpentinization, is plotted against the percentage of serpentinization, as is done in figure 14, page 117, it is seen that the proportion of iron in the ferric state steadily increases with increasing serpentinization. Figure 14 gives these data for 57 analyses of peridotites of which the unnumbered points are calculated from the superior analyses of dunite and closely related rocks given in Washington's tables (Washington (1917)). Points numbered 1 to 14 are from other published descriptions of dunite and related rocks. Points 15a and b and 16a and b are calculated from Rosiwal analyses of Blashke Island rocks, as described on page 124, and points 17 to 21, inclusive, are from the chemical analyses of dunite, augite dunite, and wehrlite given in table 2. The trend indicated by the plotted

Figure 14, References for analyses plotted

Unnumbered points	Washington, H. S., Chemical analyses of igneous rocks, U. S. Geol. Survey Prof. Paper 99, pp. 736-740 and 923-932, 1917.
Points	
1, 2, & 3	Duparc, L. and Grosset, A., Recherches geologique sur le district Minier de Nicolai Pawda, p. 56, Kundig, Geneva, 1916.
4 & 5	Wells, R. C., Analyses of rocks and minerals from the laboratory of the U. S. Geol. Survey 1914-1936, U. S. Geol. Survey Bull. 878, pp. 11 and 112, 1937.
6	Caillere, S., Contribution a R'Etude de Mineraux de Serpentines, Soc. franc. minéralogie Bull., vol. 59, p. 207, April 23, 1936.
7	Clarke, F. W., Data of Geochemistry, U. S. Geol. Survey Bull. 695, p. 461, 1920.
8	Johannsen, A., A descriptive petrography of the igneous rocks, vol. IV, p. 406, Univ. Chicago Press, 1938.
9	Daly, R. A., Igneous rocks and the depths of the earth, p. 20, McGraw Hill, 1933.
10	Barnes, V. E., Dawson, R. F., and Parkinson, G. A., Building stones of central Texas, The University of Texas Pub. 4246, Dec. 8, 1942, Austin, Texas, pp. 110-111.
11, 12	Sobolev, N. D., Ferric iron as an index of the degree of serpentinization of ultrabasic rocks, Comptes rendus (Doklady) Acad. sci. U.R.S.S., vol. 42, no. 7, pp. 301-303, 1944.
13	Cairnes, C. E., Coquihalla area, British Columbia, Canada Geol. Survey Mem. 139, p. 35, 1924.
14	Cairnes, C. E., Geology and mineral deposits of Bridge River Mining Camp, B. C., Canada Geol. Survey Mem. 213, p. 29, 1937.
15a	Calculated from mode of Blashke Island dunite assuming all iron originally present in olivine and not released as secondary magnetite is present as combined ferric iron in serpentine.
15b	Calculated from mode of Blashke Island dunite assuming all iron originally present in olivine and not released as secondary magnetite is present as combined ferrous iron in serpentine.
16a	Calculated from mode of Blashke Island wehrlite assuming all iron originally present in olivine and not released as secondary magnetite is present in serpentine as combined ferric iron.
16b	Calculated from mode of Blashke Island wehrlite assuming all iron originally present in olivine and not released as secondary magnetite is present in serpentine as combined ferrous iron.
17,18,19,20,21	Chemical analyses of Blashke Island peridotites given in columns A, B, C, D, and E of table 2.

points in figure 14 is unassailable, as rocks approach complete serpentinization most of the iron in the rock is oxidized to the ferric state. It is apparent, therefore, that the serpentinization of peridotitic rocks generally involves oxidation of most of the ferrous iron present in the primary silicates to ferric iron. This fact has been reported by Sobolev (1944, pp. 301-303), who states that 52 analyses of ultrabasic rocks from the Caucasus ranging from fresh dunite to completely hydrated serpentinite confirm this rule. Four analyses are given by Sobolev: one of fresh peridotite, one of serpentinite without primary silicates, and two of partly serpentinized peridotite. The analyses of the fresh peridotite and the serpentinite are plotted as points 11 and 12 on figure 14. The other analyses are rejected because one described as slightly serpentinized shows combined water amounting to 92 percent of complete serpentinization and the other described as intensely serpentinized (but not completely) gives combined water 10 percent in excess of that required for complete serpentinization. Sobolev states that the sum of ferric and ferrous iron oxides in peridotites generally ranges from 6 to 12 percent, and that in fresh peridotites Fe_2O_3 generally amounts to about 1 percent of the total rock, while in serpentinized peridotites the situation is reversed and FeO is generally about 1 percent of the rock. Sobolev's observations are in agreement with the analyses studied by the author.

The question naturally arises as to where this ferric iron is in the serpentinized peridotites, and why analyses of serpentine minerals commonly show iron in the ferrous state. The anomalous character of the situation is further emphasized when it is recalled that analyses of serpentine minerals very commonly show a tenor of iron of the same order as the tenor of iron in most peridotites. It is not altogether facetious to ask if petrologists are oxidizing and mineralogists reducing agents!

Sobolev (1944) has advanced the explanation that the serpentine is a pure magnesian silicate containing no combined iron, and that the opaque dust commonly observed in serpentine and generally said to be magnetite is in fact hematite formed from iron released during serpentinization of olivine and pyroxene. This explanation finds little support in the literature or in the examination of serpentine in the Blashke Island peridotites. Hematite in thin flakes and dust-like particles is translucent and blood-red in color. Finely divided hematite is a strong red coloring agent. Red coloration usually appears in serpentine only after weathering. Fresh serpentine is commonly colorless or light to dark greenish-yellow or greenish-gray. The opaque material in serpentine may easily be separated with a magnet if it is coarse enough to be freed by grinding. It seems more likely that the opaque dust that forms in serpentine is magnetite.

Two calculated curves are drawn on figure 14. The upper one shows the relationship of ferric iron to percent of serpentinization in an ideal case where all the iron in the rock is assumed to be originally in the ferrous state and is oxidized completely to the ferric state during serpentinization. The lower curve shows the relationship if all the iron assumed to be present in the ferrous state is oxidized to magnetite during serpentinization. Most of the points fall between these two ideal trends. However, allowance should be made for the fact that ferric iron was no doubt present originally in most rocks. This would cause some of the points at the lower end of the curves to fall above the curves, which were calculated with the assumption that there is no primary ferric iron. When this allowance is made it becomes apparent that the only important deviations from a position intermediate between complete oxidization and oxidization to magnetite fall below the lower curve, indicating an even lesser degree of oxidization. If serpentinization is accompanied by the formation of magnetite or some other anhydrous phase in appreciable amounts, then the percent serpentinization calculated on the basis of complete conversion to pure serpentine becomes progressively less than the actual extent of serpentinization, and all the points, especially in the upper range of serpentinization, should be shifted to the right by an amount equivalent to the percentage of anhydrous phase formed, but if the analyses give an excess of combined water over that required for serpentine, as many analyses do, the affected points should be shifted to the left. The effect of these corrections probably would bring all the points into closer agreement with the average trend that lies someplace between the curve for complete oxidization of ferrous iron to hematite and the curve for conversion of ferrous iron to magnetite.

Therefore it is concluded that most of the ferrous iron originally present in olivine and pyroxene is released during serpentinization and partially oxidized to magnetite. Sobolev's contention that the iron is completely oxidized to hematite falls down because most of the points should fall above rather than below the curve indicating complete oxidization in figure 14 if this were true. However, it is probably true that after correction most of the points in figure 14 would still lie somewhat above the magnetite trend, particularly the points representing practically completely serpentinized rocks. This indicates either the presence of some hematite or that some iron is combined in serpentine in the ferric state. In the Blashke Island complex the presence of free ferric iron is related to weathering, and some slight degree of weathering in most analyzed specimens may explain some of this deviation. However, Barnes (Barnes, Dawson, and Parkinson, 1942, pp. 110-111) has published a modern analysis of a serpentinite consisting of greenish-white to deep greenish-black serpentine with a little accessory magnetite and an unidentified fibrous mineral. The ferric oxide percentage of this analysis is plotted as number 10 in figure 14. The rock contains 6.71 percent Fe_2O_3 and 0.70 percent FeO and the composition of the serpentine is calculated by Barnes in terms of the following hypothetical molecules:

$(OH)_8Mg_6Si_4O_{10}$	85.29 percent	(antigorite)
$(OH)_8Mg_4Fe_4Si_2O_{10}$	12.98 percent	(magnesio-cronstedite) (Winchell, 1933, p. 286)
$(OH)_8Mg_4Al_4Si_2O_{10}$	1.19 percent	(amesite)
$(OH)_8Ni_6Si_4O_{10}$	0.54 percent	(nepouite)

In other words, Barnes considers the ferric iron other than that required for magnetite to be combined in the serpentine. Since the serpentinite analysis by Barnes falls close to the trend indicated by other analyses plotted in figure 14, it is not unlikely that iron entering into the composition of serpentine in serpentinized peridotites does so in the ferric state, substituting for silica as well as magnesia.

Several other modern analyses of serpentine report the iron as virtually all in the ferric state. Two analyses made by the U. S. Geological Survey laboratories (Wells, 1937, pp. 11 & 112) give nearly 6 percent Fe_2O_3 and only traces of FeO. One of these analyses is listed under analyses of igneous and crystalline rocks, the other is listed as a mineral analysis. The analyses are very nearly identical and both are from material submitted by C. S. Ross and described as serpentine of the picrolite type; the rock sample from Austria, and the mineral specimen from Bellows Falls, Vermont. Presumably the mineral sample, at least, was free of other phases such as magnetite and hematite, at any rate no notation regarding impurities accompanies the analysis. These analyses are plotted as points 4 and 5 in figure 14.

Caillere (1936,pp. 205-210) gives 45 analyses of common varieties of serpentine, of which 21 were made by herself and the rest taken from the literature. Caillere gives her analytical procedure which includes determination of ferrous iron by titration with potassium permanganate, and determination of ferric iron by subtraction of ferrous iron from total iron. She describes also in detail the method of selection of material for analysis including microscopic examination for the presence of impurities. All but two of her analyses show significant percentages of iron and all but four show ferric iron in excess of ferrous iron. The average content of Fe_2O_3 is 3.05 percent and of FeO, 1.36 percent, excluding a serpentine from Thetford with a very high Fe_2O_3 content described as associated with abundant ore. In particular she selected serpentine from Ambindavato, Madagascar, as being representative of common serpentine rock. The serpentine rock from Ambindavato consists of two kinds of serpentine; one dark green, with a mesh structure, and containing a little ore; the other light green and crumbly. The light green variety free of ore has a higher iron content than the dark green variety with some ore, so that the percentage of ore present cannot be large. The light-green variety is believed by Caillere to be due to secondary alteration of the darker variety by surface processes and gives the alpha thermal curve, while the dark variety gives the beta curve that according to Caillere is characteristic of serpentine that has not been affected by surface processes. Both contain a large excess of ferric over ferrous iron. The ferric iron percentage of the unaltered serpentine is plotted in figure 14 as point 6 and falls well within the range of the other analyses of serpentinized rock. Of the analyses of serpentine cited by Caillere from the literature most of the older ones give ferric oxide as nil and show all iron as ferrous iron, while most of the more modern ones, and particularly those by such well-known analysts as Hillebrand and F. W. Clarke, give most of the iron as Fe_2O_3.

Although the study of serpentine by Caillere is one of the most detailed and complete in the literature, another curious discrepancy is revealed in her discussion of the composition of the serpentine minerals. She describes all of the serpentines covered by the analyses discussed above as "mineraux purement magnesiens de la serpentine" (Caillere, 1936, p. 178) although her own analyses give iron up to more than ten percent. In summing up her results she states that from the point of view of chemical composition one can divide all the serpentines into two groups, pure magnesian serpentines and nickeliferous serpentines. She notes that analyses of the so-called pure magnesian group contain small amounts of alumina and suggests that it enters into serpentine by the substitution: $Al_2 \longrightarrow SiMg$, and also states that evidently aluminum can be partly replaced in this substitution by ferric iron, but fails entirely to comment on the fact that in most of her own analyses alumina is less than one percent and ferric iron is present in greater amounts. Elsewhere Caillere (1936, p. 203) remarks that variations observed in optical properties of serpentine can be explained by differences in tenor of iron. Though Caillere has for some reason neglected to recognize or fully discuss the role of iron in the serpentines that she has called pure magnesian, her own data consistently shows the presence of iron oxides up to ten or more percent, with ferric iron generally preponderant.

The evidence that has been given points to the conclusion that the serpentinization of peridotites results in the oxidation of ferrous iron originally present in olivine, some of which is released in the form of magnetite. However, it appears almost certain that an appreciable amount of the iron is retained in the serpentine, <u>but in the ferric state</u>, contrary to the common assumption that iron in serpentine is ferrous iron substituting for magnesium.

Additional support for this view can be deduced from Rosiwal analyses made on partially serpentinized dunite and augite dunite in the Blashke Island complex. Two Rosiwal analyses were calculated from modal determinations. In the calculations it was assumed that the serpentine contains combined iron equivalent to the combined iron in the olivine it replaced, less the iron required for the secondary magnetite present in the rock in particles of sufficient size to be detected microscopically in making the modal analysis.

Two sets of calculations were made: one assuming that all iron combined in serpentine is in the ferrous state, the other assuming the iron is in the ferric state. In making the calculations allowance was made for all the iron in secondary magnetite derived from serpentinization. The results are plotted on figure 14 as points 15a and b and 16a and b. Points 15a and 16a assume the iron combined in serpentine to be in the ferric state, while 15b and 16b assume the iron to be in the ferrous state. It is apparent that if the iron in serpentine is assumed to be in the ferric state the points fall perfectly within the trend shown by superior analyses of peridotite from all over the world and also are in good agreement with the chemical analyses of Blashke Island peridotite, but if the iron is calculated in the ferrous state the points fall far out of the range shown by any superior analysis of peridotite and do not compare at all with the actual chemical analyses. If the iron in serpentine is at least in part combined, as many investigators have assumed, rather than contained as a separate phase in minute inclusions, then it must be in the ferric state. Therefore determination of the composition of serpentine from optical correlations based on analyses giving iron in the ferrous state may apply to certain kinds of serpentine, but probably does not apply to the common serpentine characteristic of serpentinized peridotite.

However, figure 14 does show a few large deviations from the trend toward oxidization of ferrous iron during serpentinization that fall below the trend toward complete oxidization or oxidization to magnetite, and may not be explainable by an excess of combined water. A certain amount of combined iron in the ferrous state in serpentine, under some other set of equilibrium conditions, may explain this. The dispersion of values for the ferric oxide ratio both above and below the magnetite trend in the region of extreme serpentinization may indicate that there are two distinct sets of conditions that can result in an advanced degree of serpentinization in peridotites. Perhaps one set of conditions results in the advanced serpentinization observed in connection with weathering, and the other may be extreme hydrothermal or epi-magmatic. However, within the range of serpentinization in the Blashke Islands it seems clear that oxidation of most of the ferrous iron in olivine and pyroxene and its release in the form of magnetite or retention in serpentine as a ferric ion is to be expected.

One final question remains unanswered, and that is why so many analyses of serpentine as a mineral rather than a rock show relatively large percentages of ferrous iron and little or no ferric iron. If serpentine of this composition were characteristic of peridotites, the percentage of iron in the ferric state should show little or no increase during serpentinization. The trend shown by a graph such as figure 14 should thus fall far below that found for the superior rock analyses. There are a sufficient number of mineral analyses, particularly recent ones, of serpentine minerals giving ferric iron in excess of ferrous iron to question whether many mineral analysts have merely assumed that the iron found during analysis was combined in the ferrous state and computed their analyses accordingly. On the other hand rock analysts are generally looking for both ferrous and ferric iron and determine both values in making a superior analysis. A complete answer to the questions raised here can be obtained only by a critical review of a number of analyses and by a structural study to determine if it is reasonable to place ferric iron in the serpentine structure.

The question as to the state of iron in serpentine may be the key to the conditions under which serpentinization takes place. The field relations and petrography of the Blashke Island peridotites seem much more in keeping with the view that the primary stages of serpentinization are the result of reaction of early-formed silicates with residual magmatic water, rather than water from external hydrothermal or atmospheric sources. One objection to the auto-hydration process is that silica must be added along with water or magnesium extracted to effect the serpentinization of olivine. However, if the olivine contains iron, as it always does in peridotites, then release of iron in the form of magnetite or substitution of ferric iron for part of the silica in serpentine yields additional silica for serpentinization. If olivine contains 20 percent fayalite, for example, no silica at all need be added to balance the following hypothetical equation:

$$10(Mg_{0.8},Fe_{0.2})_2SiO_4+12H_2O+O_2 \leftrightarrow 2(OH)_8Mg_6Si_4O_{10}+(OH)_8Mg_4Fe_4Si_2O_{10}$$

(olivine, Fo80Fa20) (antigorite) (magnesiocronstedite)

If olivine contains 25 percent fayalite the following hypothetical equation may be balanced without additional silica:

$$12(Mg_{0.75}Fe_{0.25})_2SiO_4+12H_2O+O_2 \longleftrightarrow 3(OH)_8Mg_6Si_4O_{10}+2Fe_3O_4$$

(olivine, Fo75Fa25) (antigorite) (magnetite)

Furthermore petrographic evidence strongly indicates that serpentinization is a volume for volume process of replacement, and therefore some part of the original heavy phase, olivine, must be removed to make way for an equal volume of the lighter phase, serpentine. It is reasonable to assume that it is magnesium that is carried away, and this further reduces the necessity for introducing silica.

The source of oxygen needed to oxidize iron during serpentinization presents no problem and does not require the introduction of oxygen from any external source. Kennedy (1948, pp. 529-549) has recently published data on the equilibrium between iron oxides and oxygen. Kennedy gives experimentally determined values for the dissociation constant in the reaction $2Fe_2O_3 \leftrightarrow 4FeO+O_2$ at temperatures from 1200°C. ot 1400°C. He shows that theoretical values agree with an extrapolation of experimental values down to 800°C. Perhaps a further extrapolation of Kennedy's values to lower temperatures introduces considerable error, but if his values are extrapolated into the stability range of serpentine (below about 500°C.) given by Bowen and Tuttle (1950, pp. 439-460) and compared with the partial pressure of oxygen resulting from the dissociation of water (Dwyer and Oldenberg, 1944, pp. 331-361) in the same temperature range, it is seen that the equilibrium concentration of Fe_2O_3 ranges from several times to hundreds of times the concentration of FeO at pressures ranging from one to a thousand atmospheres. Even if these data merely crudely approximate the true equilibrium conditions, it means that the oxygen concentration resulting from the dissociation of water alone is adequate to oxidize most of the iron to the ferric state during serpentinization. The utilization of the oxygen resulting from the dissociation of water should consequently result in an excess of free hydrogen, and it is interesting to note that Zavaritsky (Zavaritsky and Betekhtin, 1937, p. 72) reports a large concentration of H_2 in the gases emerging from a hole drilled to a depth of 600 meters in dunite. Further investigation of the equilibrium relations of the iron oxides and oxygen in the stability range of serpentine may make it possible to calculate the temperature and pressure range of water vapor within which serpentinization takes place.

In summary, in the process of serpentinization as observed in the Blashke Island rocks and in the light of the foregoing discussion, there appears to be more than one stage in the development of serpentine and several distinct phases may be present simultaneously in the serpentine. Initially serpentine appears in a network of veinlets along fractures in the olivine throughout the complex. It has been shown that these veins are formed by the replacement of olivine along pre-existing fractures and that the formation of these veins post-dates all movements involved in the emplacement of the complex. This serpentine shows an increase in refringence, birefringence, and pleochroism with increasing iron content in the olivine it replaces, and when the iron content of the olivine reaches a minimum value near 12 to 13 percent fayalite its formation is accompanied by the release of iron oxide in the form of dusty magnetite. The variation in optical properties is probably caused by variation in the tenor of combined iron, which is probably in the ferric state. This stage of serpentinization is present throughout the complex and bears no relationship to the extent of weathering, so far as can be judged by the relative freshness of the rock and its relationship to joints, shear zones, and other features that control weathering.

In the second stage very low-birefringent serpentine forms along the medial partings in the initial veinlets, accompanied by spongy secondary magnetite, where the olivine contains 11.5 percent or more fayalite. This serpentine has low indices and probably represents an iron-poor or iron-free phase formed from the initial iron-bearing serpentine with the release of iron in the form of spongy magnetite. This stage is present in most rocks of the complex containing abundant olivine and bears no observable relationship to weathering.

Alteration that may be in part related to weathering results in the more or less complete replacement of olivine shards by a felted mass of disoriented serpentine ranging from almost isotropic material to material with anomalous first order interference colors and from almost colorless to green in thin section. The properties of this material are those of low alumina chlorite. This stage of serpentinization is sporadically developed throughout the complex and seems correlated to some extent with more iron-rich olivine and with surficial alteration.

A type of alteration definitely related to weathering is the development of amber discoloration in previously formed serpentine, accompanied by an increase in refractive indices. This is interpreted as being caused by the release of colloidal ferric oxide in a further breaking down of ferriferous serpentine. However, previously formed magnetite is not necessarily oxidized to hematite or limonite at the same time.

Serpentinization, it appears, is not a simple, one-stage process, but involves the formation of a primary serpentine that may contain iron proportional to the iron in the olivine from which it formed, followed by the breakdown of this material into two or more phases that may include pure antigorite or chrysotile, magnetite, hematite, colloidal ferric oxide, and iron-rich chlorite.

Chlorite

Many thin sections of serpentinized dunite, augite-dunite, and wehrlite contain traces of colorless chlorite as a distinct, but quantitatively negligible, phase in the serpentine. The mineral is colorless in thin section but is pale bluish-green in visible crystals and large fragments under the microscope. It has perfect micaceous cleavage and cleavage flakes are flexible but not elastic. Optical properties:

Acute bisectrix Z approximately normal to c(001).

2V variable within a single crystal from nearly zero to about 20°.

Distinct dispersion of optic axes with r less than v.

Birefringence, 0.003 to 0.004 with anomalous brownish to bluish interference colors.

Ny approximately equal to Nx = 1.587 ± 0.002.

According to Winchell's (1933, p. 280) optical classification of the chlorites this mineral falls in the positive penninite range. Except for lower birefringence it agrees closely in properties with clinochlore that is common in serpentine in the Quebec "serpentine belt" (Poitevin and Graham, 1918, pp. 64-65).

White chlorite is present in the serpentine in small, irregular shred-like grains without crystal form. The grains appear to make no sharp boundary with serpentine, but pass through an isotropic border zone and merge into the surrounding serpentine with continuity of cleavage traces as though gradational with the serpentine. The chlorite appears to be later than the early serpentine but to belong to the end of the initial period of serpentine formation. This relationship tends to substantiate Winchell's (1933) contention that there is an isomorphous relationship between chlorite and serpentine.

The presence of this aluminous phase at this stage is significant in that it indicates that a small amount of alumina was a component of late aqueous solutions in the dunite. The presence of an aluminous hornblende and a little plagioclase feldspar in the olivine augitite indicates that the concentration of alumina attained a higher value at an earlier stage in the pyroxene-rich rocks.

White chlorite is also present in coarse well-formed crystals in a few thin veinlets that were observed in several localities near the dunite augitite contact. These veinlets are no more than 5 millimeters wide and a few meters long. The white chlorite is in crystals as wide as the veins and in some veins the crystals are crumpled so that the trace of the cleavage in thin section has a zig-zag pattern. Commonly lenticular blebs of calcite and magnetite occur within the crystals along the cleavage. In these veins the white chlorite is associated with felted, disoriented serpentine and with calcite. The presence of white chlorite in veinlets formed at a very late stage suggests that the alumina necessary to form this phase was introduced into the peridotite from outside.

Common green chlorite ranging from penninite to clinochlore is a common alteration product in the gabbroic rocks. Some occupies angular interstices between primary silicates and may be late primary in crystallization. Most of the chlorite has deep blue to purple anomalous interference colors.

Chlorite is a major constituent of the country rocks surrounding the complex where they are not affected by contact metamorphism.

Talc

Talc is present only in late veinlets a fraction of a millimeter wide and a few centimeters long cutting the other serpentine minerals and in a few irregular areas where it replaces serpentine. The veinlets are very small and widely scattered, forming an insignificant percentage of the rock. The veinlets occupied by talc have the appearance of small gash fractures. Displacement of microscopic magnitude may be observed along some of them. Others are very irregular and follow crooked paths through the rock skirting the margins of olivine and augite grains without replacing the primary silicates. The formation of talc took place after the initial stages of serpentinization at least had been completed. It is so sporadic in occurrence and present in such small amounts that its formation either came in the dying stages of the sequence of processes involved in the formation of the complex or is the result of subsequent unrelated hydrothermal activity of a very weak order.

Talc has also been observed as an alteration product of hypersthene in gabbroic granulite and contaminated gabbro.

Leucoxene

Calcic plagioclase in the Blashke Island rocks is locally altered to a dead white, cryptocrystalline, powdery substance that is opaque to dark brown with extreme refringence in transmitted light. This kind of alteration is commonest where plagioclase is present in minor amounts as a disseminated late phase in marginal facies of the olivine augitite, but it is not uncommon in much of the gabbro that contains a highly calcic plagioclase. This mineral is identified as leucoxene. Its occurrence parallels the presence of appreciable titanium in the rocks as shown by the chemical analyses in table 2 and the variation diagram, figure 16 , page 152 . It is noteworthy that titanium is most abundant in aluminous rocks that are high in calcium, because alteration to leucoxene is probably brought about by deuteric attack on calcic plagioclase by titanium-bearing residual fluids concentrated along with the calcic aluminous phase, plagioclase.

Locally a little hornblende is altered to leucoxene along with plagioclase.

Zoisite, clinozoisite, and epidote

These minerals are present in the complex only as secondary products of deuteric alteration or later hydrothermal attack. They are confined in occurrence to the feldspathic rocks and are largely derived from the alteration of plagioclase. Members of this group of minerals are a principal constituent of saussurite, and saussurite is one of the common alteration products of the more calcic plagioclase in the gabbro. Much of the alteration of plagioclase to zoisite, clinozoisite, or epidote can be traced to small shear zones and fractures that cut the rock.

Zoisite, clinozoisite, and epidote are not uncommon in the lower ranks of contact metamorphosed country rock around the complex.

Prehnite

Some slides of gabbro contain measurable percentages of prehnite. The prehnite is colorless to faintly yellowish-green in thin section and is found as coarse grains occupying angular interstices between developed crystal faces of the principal primary minerals. It is probably of very late primary crystallization. In a few slides such as specimen 104, item 131 , table 1, prehnite makes up several percent of the rock, both as a late interstitial mineral and as an alteration product of plagioclase. Prehnite formed by the alteration of plagioclase is found disseminated through the rock and also in sheared areas and along hydrothermally altered fracture walls.

Heulandite

One thin section of gabbro, specimen 120, item 127, table 1, contains areas of altered plagioclase consisting of epidote and an optically positive mineral with small optic angle and negative relief. The optic orientation with respect to traces of cleavage corresponds to heulandite, and it is tentatively identified as heulandite although none was isolated for positive identification. It is present only in traces in very small grains and appears to be a deuteric alteration product of plagioclase feldspar.

Calcite and other carbonates

Calcite is present as a gangue in a few veins cutting peridotitic rocks and not more than 3 millimeters wide, containing serpentine and the coarsely crystalline white chlorite described above. In view of the magnesian character of the rock and of the other minerals in the veins it might be anticipated that any carbonate present would be magnesite or dolomite. However, the mineral effervesces vigorously in dilute hydrochloric acid and the index No = 1.658, leaving little doubt as to its identity. These calcite-bearing veinlets may also be the result of weak hydrothermal activity post-dating the complex. However, waters containing carbonate ion attacking the rock would be expected to produce a magnesian carbonate and might not be expected to produce the white chlorite and serpentine associated with the calcite. On the other hand the sequence of minerals forming in the complex points to a steady enrichment of the late fluids in calcium, aluminum and iron so that magnesium may have been quantitatively removed from the fluid phase at the close of activity. The veinlets are found cutting augite-dunite and wehrlite in close proximity to the dunite-augitite contact. They are not found deep within the dunite core or in the center or the outer margins of the olivine augitite ring. They are not found associated with any of the observable zones of shearing and faulting affecting the complex.

Carbonate is common in the country rocks surrounding the complex. It is very abundant in the altered volcanics where it appears disseminated through the rock and as pseudomorphs after augite. Some of the conglomerates consist of limestone and marble boulders in an impure limey matrix and some beds up to 30 feet thick of coarse white to buff marble are present.

Coronas and coronites

Coronas have been defined by Shand (1945, pp. 247-266) as reaction rims between two different minerals in which a sheath or shell of new minerals or a new mineral generated by the reaction forms between and about the reacting grains. Coronas of several different kinds are developed locally in some Blashke Island rocks.

The most common coronas in the Blashke Island rocks are found in olivine gabbro and consist of pale, clear green amphibole shells around olivine in contact with plagioclase. In most of the pale amphibole coronas some hypersthene is present, but the hypersthene is sporadic in distribution and some olivine grains in the rock have complete shells of pale amphibole alone, while others have partial shells of pale amphibole with a discontinuous inner shell of hypersthene. Other grains of olivine in the same thin section have no coronas at all and are in sharp contact with plagioclase. The hypersthene in these coronas is very commonly, but not without exception, intergrown with abundant magnetite in a graphic pattern. Rocks containing coronas of olivine - pale amphibole - plagioclase, olivine - hypersthene - pale amphibole - plagioclase, or olivine - hypersthene - magnetite - pale amphibole - plagioclase include specimens 142, 219, 308, and 220, items 118, 119, 122, and 120, table 1. Photomicrographs showing examples of these coronas are plates 26B, 27A, 27B, and 28A.

A second kind of corona is found in the same rocks as the olivine - amphibole - plagioclase coronas described in the preceding paragraph, and consists of pale amphibole shells between augite and plagioclase. The amphibole is identical in properties with that surrounding the olivine, and in fact contiguous grains of olivine and augite are commonly surrounded together by a rim of crystallographically continuous amphibole. Good examples are seen in the photomicrographs cited in the preceding paragraph. The pale amphibole that forms these coronas is different in properties from the hornblende commonly present in coarse, poikilitic grains and replacing augite in these rocks. The latter variety of hornblende is strongly pleochroic in yellowish to brownish green.

A third kind of corona is found in several hornblende-rich beerbachites containing a few coarse phenocrysts of olivine. These coronas consist of a jumbled, granular aggregate of small hypersthene grains forming a shell around the olivine separating it from hornblende. Specimens 207 and 214, items 114, and 113, table 1, contain coronas of this kind.

A fourth kind of corona consists of shells of augite surrounding hypersthene where the hypersthene forms inclusions in coarse poikilitic hornblende. Specimen 347, item 123, table 1, contains coronas of this kind, pictured in plate 28B.

A distinction can be made between the rocks that contain coronas between olivine and plagioclase and the rocks that contain olivine and plagioclase without coronas. The coronas are found only in the olivine gabbro. No coronas are found between olivine and plagioclase where the plagioclase is disseminated interstitially in certain facies of the peridotite, or in the gabbroic pegmatite bodies in the olivine augitite, or in olivine beerbachite dikes. No coronas are found around the iron-rich olivine in the gabbroic granulite and gabbroic granulite is excluded in the following discussion.

In general the olivine in the gabbro is richer in iron and the plagioclase is slightly less calcic than the olivine and plagioclase in the peridotite, gabbroic pegmatite, and olivine beerbachite. However, the difference in composition between the olivine and the plagioclase in the coronites and the olivine and plagioclase in the non-coronites is actually very slight with some overlapping as shown by the following table.

Table 7.

Composition of olivine and plagioclase in coronites and non-coronites of the Blashke Island Complex

Specimen No.	Item No. table 1	Olivine		Plagioclase		Remarks
		Fo	Fa	Ab	An	
Coronites:						
142	118	75.5	24.5	5	95	Olivine later than some of the plagioclase
219	119	74	26	7	93	Olivine later than some of the plagioclase
308	122	ND		7	93	Late poikilitic plagioclase
220	120	ND		20	80	Late poikilitic plagioclase
Non-coronites:						
247	43	85.5	14.5	6	94	Feldspathic wehrlite
167	98	81.5	18.5	6	94	Feldspathic wehrlite dike
333	104	78	22	6	94	Olivine beerbachite
244	100	77.5	21.5	4	96	Gabbroic pegmatite in olivine augitite
215	81	77.5	21.5	anorthite		Olivine augitite with accessory plagioclase
334	105	77	23	6	94	Olivine beerbachite
367	106	76.5	23.5	9	91	Olivine beerbachite
216	83	74	26	anorthite		Feldspathic olivine augitite grading into gabbro, specimen 219 above.

(ND = Composition not determined because grains could not be isolated.)

Shand (1945, pp. 258-262) has described an enstatite coronite from Quebec from a complex containing olivine-rich rocks approaching peridotite in the core. The composition of the olivine reported by Shand is Fa24 and the plagioclase is An47. Shand notes that only one specimen out of a number from the complex contained coronas, but he gives no data on the composition of the olivine and plagioclase in the corona-free rocks. However he notes that coronas are associated with rocks rich in iron. Shand attributes the formation of coronas to thermal metamorphism acting on rocks of suitable composition. The field relations in the Blashke Islands give little evidence for thermal metamorphism subsequent to the thermal processes associated with the formation of the complex itself, and no evidence that the rocks that contain coronas have been subjected to more post-magmatic heat than the rocks with similar mineral content that do not contain coronas.

Two conditions appear on the basis of the limited data available to control the development of coronas between olivine and plagioclase in the Blashke Island complex. One is the composition of the olivine, which in association with a highly calcic plagioclase apparently must contain 24 percent or more fayalite. The other is the geologic mode of occurrence, in that only olivine gabbros within the gabbro ring of the complex have coronas. It is suspected that this latter condition is related to the concentration of late magmatic fluids in the rock. Examples have been seen in thin section where an olivine grain contains an inclusion of plagioclase about which there is no corona, while the external contacts of the olivine with plagioclase are rimmed by a corona. The gabbroic granulite is notably free of hydrous phases and is also free of coronas, although the composition of both olivine and plagioclase should be conducive to their formation, if the foregoing discussion is correct.

No generalizations can be made about the other kinds of coronas described above, except that the enstatite coronas between olivine and hornblende are found in a couple of hornblendite-beerbachite dikes of a kind that does not normally contain olivine. The olivine is present in a very few unusually large phenocrysts that may have been incorporated from the peridotites that the dikes traversed. Therefore the phenocrysts, or xenocrysts, as they might be styled, may not have been in equilibrium with the crystallizing ground mass. The augite coronas around enstatite inclusions in poikilitic hornblende are unique in one specimen of a coarse, uneven textured rock forming a dike-like body in hornfelsed country rock on the west side of the complex, and the actual magmatic origin of this rock is subject to some question.

Dike rocks older than the complex

Throughout the Blashke Islands the stratified country rocks are cut by numerous dikes. These dikes are commonly steeply dipping, though a few have gentle dips, and they cut sharply across the bedding in the stratified country rocks. In a crude way they follow two main trends, northeast-southwest and northwest-southeast. Detailed mapping of lithologic units in the country rocks exposed along the shores of the islands has proved in several localities that some of these dikes occupy faults along which displacements on the order of hundreds of feet have taken place before emplacement of the dike. Other dikes in the same localities occupy fractures along which there has been little or no displacement. The dikes range in thickness from a few inches to tens of feet. Some of the dikes are exposed continuously for several hundred feet without exposing their entire length. Others are lenticular in outcrop and pinch out gradually at both ends in tens or hundreds of feet. Linear flow structure shown by preferred orientation of phenocrysts and inclusions is not uncommon.

The dikes exhibit some petrologic variety but for the most part fall within the range of basaltic andesite and basalt. In hand specimen they are aphanitic to microphaneritic and commonly porphyritic. A few are medium-grained phanerites. They are mostly dark gray and greenish gray in color but medium greenish-gray varieties are not uncommon. Generally the minerals in the groundmass cannot be identified in hand specimen, but where porphyritic, phenocrysts of pyroxene, hornblende, and plagioclase, can be recognized. Sparcely disseminated sulfides are not uncommon.

In thin section, the dikes range in texture from ophitic and sub-ophitic to diabasic and sub-diabasic. The plagioclase crystals are generally lath-shaped in the groundmass and are imbedded in a mesostasis of one or more ferromagnesian minerals. The following typical mineral associations have been found: (1) plagioclase and green hornblende, (2) plagioclase, green hornblende, and augite or augite and hypersthene, (3) plagioclase, green hornblende, and biotite, (4) plagioclase, green hornblende, pyroxene, and biotite, (5) plagioclase and biotite. Biotite is not common except in dikes of this group found within 1,000 feet of the ultrabasic complex where it is generally accompanied by the development of noticeable granulitic texture indicating that it is a product of thermal metamorphism by the complex. However one narrow, fine-grained dike located over 2,000 feet from the complex contained a few relatively coarse hornblende phenocrysts in a diabasic groundmass of plagioclase in which abundant biotite appears to proxy for the more common ferromagnesian minerals, and this is presumed to be a primary feature. In general the mineralogy of the dikes is very simple with disseminated ore the only important accessory.

The most common porphyries contain relatively large, well-formed phenocrysts of either augite or hornblende, not both together. Smaller phenocrysts of sharply zoned plagioclase may also be present. A few plagioclase porphyries with subordinate ferromagnesian phenocrysts have been noted. Amygdules containing calcite, quartz, and prehnite have been found. One or two dikes studied in thin section have a few rounded patches of antigorite that may be pseudomorphs after olivine.

The plagioclase ranges in composition from sodic bytownite to calcic andesine with sodic labradorite the most common. The augite has a distinct yellowish tint but is not strongly pleochroic nor does it have noticeable dispersion. Its optic angle is moderately large. Hypersthene is not common, but where present has a moderate negative optic angle.

These rocks generally show distinct to strong alteration. Beyond the zone noticeably affected by intrusion of the ultrabasic complex this alteration generally consists of chloritization and replacement by carbonates and secondary quartz and albite. Some degree of amphibolitization may also be due to regional metamorphism, but amphibolitization becomes much stronger as the complex is approached and it is difficult to say how far beyond the complex this effect can be attributed to contact metamorphism.

As the complex is approached amphibolitization becomes very noticeable in the dikes, and in many of them the groundmass is converted into a ragged aggregate of green hornblende with only remnants of the original plagioclase laths. Within a few hundred feet of the complex granoblastic aggregates of biotite replace some of the hornblende. Several specimens examined in thin section collected from dikes within a few yards of the outer margin of the gabbro ring of the complex along the eastern side show strong to complete granulitization. The contact metamorphic effects produced on this group of dikes by the complex proves that they antedate the complex, and if genetically related to the complex must be forerunners of the ultrabasic intrusion. The youngest rocks cut by them in the Blashke Islands are Silurian. Their correlation with other intrusions is not known.

A chemical analysis is given for a dike rock of this group. The specimen selected for analysis came from a hornblende porphyry dike about 4 feet wide cutting a coarse conglomerate. The dike has a distinct linear flow structure shown by a noticeable preferred alignment of hornblende phenocrysts. The dike also contains abundant inclusions of country rock. The groundmass of the dike originally consisted of a sub-ophitic aggregate of plagioclase and a ferromagnesian mineral. Amphibolitization has given the groundmass a very ragged texture, and it consists of plagioclase and alteration products with abundant fine-grained pale amphibole. The feldspar is partially altered. A few small phenocrysts of feldspar are present. They are strongly zoned and the inner zones range up into bytownite. A little penninite is present in thin veinlets, a few amygdaloidal grains of quartz were noted, and among the alteration products present in small percentages are: actinolite, penninite, zoisite, albite, muscovite, sericite, and leucoxene. The analysis appears under column 8 of table 2 with the norm and mode. In chemical composition it falls within the range of many common saturated dolerites.

Dikes younger than the complex

Near the entrance to Spud Bay on the southwestern side of the complex the dunite is cut by several dikes up to 5 feet wide. The dikes are aphanitic and weather almost the same color as the dunite, but the jointing and surface texture is distinctive. Dikes of the same rock outcrop near the lower end of Trap Bay where they cut thin bedded to conglomeratic low-grade metamorphosed argillites. These dikes are the only consolidated rocks found in the area younger than the complex.

The rock is very dark brownish-black in hand specimen, weathering to a smooth reddish-brown. Th texture is aphanitic. Amygdules of calcite and zeolites are abundant. In thin section the rock has an intersertal hypocrystalline texture made up of abundant laths of plagioclase, small, well-formed crystals of titanaugite, and abundant, small, sub-rectangular grains of ore - probably ilmenite - in a base of yellowish-brown glass. The cores of zoned plagioclase are sodic labradorite. The titanaugite has a moderately small optic angle, strong dispersion, and a distinct lavender tint. A chemical analysis, norm, and mode for this rock are given under column 22 of table 2.

This rock compares closely with the petrographic descriptions given by Buddington (Buddington and Chapin 1929, p. 273) for several dikes of Tertiary age from nearby islands. The rock is chilled against the dunite of the Blashke Island complex, and so there is little doubt that it belongs to the Tertiary basalts and andesites recognized by Buddington. The chemical analysis shows it to be a somewhat alkalic, distinctly oversaturated andesite-basalt melaphyre. It is believed to have no genetic connection with the complex.

Structure and deformation of the complex and surrounding rocks

The lower Paleozoic rocks invaded by the Blashke Island complex underwent strong folding and some metamorphism in at least two different periods prior to the intrusion of the complex. Subsequent to the folding, high angle faulting and some minor thrust faulting took place and many of the faults and fractures stemming from this early period were invaded by doleritic dikes. The area falls within the province of a major structure that Buddington (Buddington and Chapin, 1929, pp. 310-311) has called the Kashevarof anticlinorium described by him as a northward-plunging major structure in which the sequence of formations is repeated many times by close folding.

No evidence is seen in the Blashke Islands for an unconformity between the Ordovician rocks and the lower of the two Silurian sequences that overlie the Ordovician. These two units are lithologically gradational in a broad sense and appear to have been folded and metamorphosed together. Throughout the islands they stand at high dips and their attitude changes abruptly from place to place indicating close folding.

The overlying Silurian unit appears only in two limited areas at the northern end of the Islands. The attitude of this sequence of rocks and the fact that it appears in contact with both the Ordovician rocks and the older Silurian rocks indicates that a pronounced unconformity intervenes between the two Silurian units. Strong supporting evidence is seen in the lithology. The lower of the Silurian units is somewhat metamorphosed and contains at least one bed perhaps 30 or 40 feet thick of moderately coarse, completely recrystallized white marble. Outcrops of this marble were found far beyond the range of contact metamorphism effected by the complex. The upper of the two Silurian formations on the other hand consists in part of laminated to thin-bedded, dove-gray to white limestone having a fracture cleavage where somewhat shaley but showing no evidence of recrystallization. However, this formation has also been strongly folded. All of the Paleozoic rocks are cut by faults and dikes belonging to a sequence older than the ultrabasic complex.

The intrusion of the complex appears to have caused further deformation. Buddington (Buddington and Chapin, 1929, p. 310) states:

"On the Blashke Islands the beds are domed up by an intrusion of dunite and associated dioritic (i.e. gabbroic) rocks, and Ordovician graywacke is exposed on the borders of the igneous stock within a belt of the Silurian greenstone."

The dome-like relationship is true in a broad, general sense, the intrusion of the complex apparently having either caused an upheaval of the sequence into which it was emplaced or having followed some structure previously produced by a strong transgressive mass. The abundance of pyroclastic material in the lower of the Silurian units suggests that if a preexisting structure was used it might well have been an old volcanic vent. In detail the structure is a good deal more complicated than a simple dome. Deformation becomes strong in the vicinity of the complex. In general the attitude of the bedding swings into crude conformity with the outlines of the complex but there is much crumpling, disturbance, and obliteration of bedding. The bedding does not form a simple dome-like sheath around and over the complex. Locally beds seem to strike into the complex and be cut off, but metamorphism near the complex makes this hard to prove. The evidence indicates that the complex is strongly transgressive, but at the same time has had a powerful upward-dragging effect on the rocks it traversed.

The internal structures of the complex have been described in connection with the description of the rock units and their relationships to one another, pages 16 to 58 . The orientation of banded or thinly layered structures in the gabbro is shown on the geologic map by a symbol and by the alignment of the dashes used to designate this rock. Weathering locally brings out a crude platy or slabby structure in the olivine augitite, wehrlite, and augite dunite. Where this structure is pronounced it is indicated by a symbol on the map. The relationship of this structure to the configuration of the complex is not understood, but in a very crude and locally self-contradictory way it has a rude dome-like pattern. Very similar ultrabasic complexes described by Duparc (Duparc and Grosset, 1916, p. 227) and Camsell (1913, p. 68) show definite evidence that a dome-like shell of pyroxenite originally completely surrounded the dunite. Camsell aptly likens the structure to a hard-boiled egg with a yolk of dunite enclosed in pyroxenite.

In the outcrops of pyroxenite along the western side of the inner Blashke Lagoon some small bosses of dunite a few yards across appear beneath what is at least locally a gently dipping undulating contact between dunite and pyroxenite. The narrow exposures of olivine augitite in contact with granulitized country rock on the main island at the northwestern edge of the complex seem to show the augitite dipping at a moderate angle beneath the altered country rock. The exposures are not good enough to be completely sure. The sum total of the evidence points toward the complex being a steep-walled cylindrical mass with many local protuberances and reentrants both horizontally and vertically. This cylindrical structure probably passed into a steep domal structure not far above, and locally at, the present level of exposure.

Except for faulting, the Blashke Island complex has escaped significant deformation subsequent to its formation. A strong series of northwest to north-trending faults has caused horizontal displacements of as much as 1,000 feet in some of the contacts between rock units in the complex. There is no way of estimating the amount of vertical movement. It may have been very large, or the faults may be largely tear faults. Where these faults pass into the ultrabasic rocks broad shear zones of closely spaced sheeted/fractures are formed and some strong faults apparently die out in this kind of structure. Locally very striking breccia zones and fault breccia conglomerates have been developed. Strong faulting and shearing has cut out and obscured some of the contact between the complex and the enclosing rocks on the southwest border of the complex. A remarkable fault breccia conglomerate consisting of augite dunite and dunite fragments in a pulverized and serpentinized dunite matrix is shown in plate 14. This breccia outcrops on the western edge of the most southerly island included in the complex. This and other shear zones are indicated by a symbol on the map.

The faulting is believed by the author to be Tertiary in age and later than the Tertiary dikes that cut the complex. These dikes appear to have been displaced by the faulting. This system of faults has had a strong control on the erosion of the Blashke Islands evidenced by the numerous inlets and bays that follow its trend.

The system of Tertiary faults proved to exist on the Blashke Islands may throw considerable light on a problem of southeastern Alaska geology that has excited some interest, namely the structural control for such major features as Clarence Strait. The islands lie in the middle of Clarence Strait and the fault system parallels the trend of the strait. The strait may have been controlled by a prolongation of this closely spaced system of Tertiary faults.

The last structural event, or geological event for that matter, recorded on the Blashke Islands is something on the order of 10 to 20 feet of post-glacial uplift. At several points on the islands, notably on the north end of Bivouac Bay, there are unconsolidated banks of lignitic mud containing abundant shell fragments of recent aspect lying 10 to 20 feet above present tide level. These shell beds must have been formed and uplifted since glacial times because they could not have withstood destruction during glaciation. Buddington (1927, pp. 45-52) has described numerous sea-cut platforms uplifted since glacial times by about the same amount throughout southeastern Alaska.

Summary of the petrology and mineralogy of the Blashke Island complex

The most obvious feature of the Blashke Island complex is the arrangement of major rock units in concentric rings with the most mafic rocks in the core and successively less mafic rings outward. Each succeeding ring is marked by the appearance in essential proportions of new mineral phases. The core of dunite contains olivine as its only essential primary phase. Augite is the dominant phase in the olivine augitite ring. Plagioclase, and to some extent hornblende, play the leading roles in the gabbro ring. Hypersthene and biotite appear in the gabbroic granulite, and the granulites grade outward into greenstone volcanics and sediments of low metamorphic rank.

However, within this large scale concentric zonal arrangement of rock types there is a hidden zoning that expresses itself in a shift, not only in the kinds and relative proportions of mineral constituents, but in the compositions within each solid solution series that comprises a mineral phase. Thus the olivine becomes poorer in magnesium and richer in iron. Augite becomes poorer in magnesium and richer in iron also, and the same trend is apparent in orthopyroxene, hornblende, and biotite. Calcium comes in as a major chemical component in augite and then in plagioclase, but the augite becomes poorer in calcium toward the iron-rich end of its variation, and the plagioclase becomes poorer in calcium and richer in sodium. So each major rock unit of the complex is not uniform within itself, but undergoes a shift in the composition of its constituent phases. This feature of the complex was first noted by George C. Kennedy in the preliminary investigation of the complex (Kennedy and Walton, 1946, p. 77).

This kind of shift in the composition of the minerals paralleling the development of a layered arrangement of rock types was noted by Wager and Deer (1939b) in the Skaergaard complex and dubbed "cryptic layering". It would seem appropriate to adapt this term to a concentric zonal arrangement of rock types and call the shifting mineral composition within the rock units of the Blashke Island complex, "cryptic zoning." Since the word zone does not have any special structural implications, the term cryptic zoning can be applied to any systematic variation in the composition of a mineral phase or phases related to a non-stratiform, genetically related, systematic arrangement of rock units.

Because of the cryptic zoning, each major rock unit in the complex is not strictly discreet and sharply defined, as would appear from the simple petrology of the complex. There is a hidden gradation in the composition of the component phases within each zone that is continuous with respect to each phase throughout the complex. Thus there is a unity to the complex as a whole that transcends the boundaries between rock types.

The effect of the cryptic zoning in the Blashke Island complex is to cause the minerals of each solid solution series to become enriched in its less refractory components the further it is found from the center of the complex, so that the range of temperature in which each phase is stable becomes progressively lower from the center of the complex outward. This progression from high-temperature rock components toward lower-temperature rock components is further expressed by the appearance of additional phases characteristic of lower temperatures such as orthoclase feldspar, quartz, and sulfides in the outer margins of the complex. However, even the outermost rocks of the complex have produced strong contact metamorphic effects on the enclosing rocks and are scarcely to be thought of as low-temperature rocks in the ordinary sense of the word.

On the other hand the concentric zoning of the complex is not perfect either in regard to the distribution and homogeniety of rock types or in regard to the cryptic zoning. An overall asymmetry of the complex has been described, and in detail within each zone of the complex there are many imperfections and anomalies in the concentric arrangement of rocks. These imperfections and anomalies fall into the following categories:

1. Imperfectly gradational to sharply discontinuous contacts between the dunite core and the olivine augitite ring.
2. Inclusions of augite-rich rock in olivine-rich rock along the contacts between dunite and olivine augitite.
3. Dikes of wehrlite and augite dunite cutting both the dunite of the core and the olivine augitite ring.
4. Dikes of augitite in augite dunite and wehrlite.
5. Sporadically distributed dikes and irregular masses of gabbroic pegmatite in augite dunite.
6. Gabbroic to hornblenditic dikes of the beerbachite group in olivine augitite and gabbro.
7. Inclusions of country rock in olivine augitite.

8. A sharp discontinuity and zone of weakness along most of the contact between gabbro and olivine augitite.

9. The local absence of the gabbro ring, and the presence of a slightly feldspathic wehrlite at some contacts between peridotite and country rock.

10. Strong textural and mineralogical variations in the gabbro in various parts of the complex.

11. A strong contrast between the well-defined intrusion breccias and other features characteristic of sharp intrusive contacts along parts of the contact between gabbro and country rock, and the vague, almost gradational contacts in other places.

12. Variations in composition in the gabbroic granulite produced by contact metamorphism of country rocks.

13. Outlying dikes of gabbro and pyroxenite.

Furthermore the cryptic zoning within the major rock units is far from perfect. The change in composition of olivine is abrupt near the contact between dunite and olivine augitite, and gradual within each of these units. A glance at the dispersion of values for the composition of olivine as correlated with relative position in the complex shown in figure 8, on page 63, shows that there is a tendency toward cryptic zoning in olivine rather than a perfectly developed gradation outward in olivine composition. The same is true of the other phases. Some of this dispersion of values may be due to observational errors, but some is surely real. The augite dunite and wehrlite dikes in dunite and olivine augitite are anomalies in the cryptic zoning. The composition of the mineral phases in these dikes corresponds not to the rock in which they are emplaced, but to the marginal facies of the dunite core. The beerbachites and gabbroic pegmatites in the olivine augitite are also anomalous with respect to the cryptic zoning in that they consistently contain olivine and augite richer in iron than the host rock.

A strong concentric zoning of major rock types is obvious from a glance at the geologic map of the Blashke Island complex. A corresponding tendency toward cryptic zoning in mineral composition has been shown to exist. A tenable theory of origin of the Blashke Island complex must explain both the concentric arrangement of rock types and the cryptic zoning, but it must explain equally well the anomalies and imperfections in the configuration of the complex.

Chemical relationships

The zoning of the complex is reflected in the trends in chemical composition of the rocks. Chemical analyses of 12 rocks belonging to the complex, an outlying gabbroic dike rock doubtfully related to the complex, and an andesite-basalt melaphyre belonging to a group of Tertiary dikes unrelated to the complex are given in table 2. Variation diagrams of the major and minor components are given in figures 15 and 16.

In these variation diagrams the molecular ratios of the constituent oxides are plotted against the molecular ratio of silica plus alumina. The reason for plotting the oxides against silica plus alumina rather than against silica alone is because the sequence of rocks includes peridotites that are virtually non-aluminous, and feldspathic rocks with substantial percentages of alumina. Some alumina is present in minor amounts in augite and perhaps other minerals, but most of it is present in plagioclase where half of the aluminum atoms substitute for silicon in the structure. If the molecular proportions of silica alone are considered, a sharp break occurs in the variation diagram between the feldspathic and non-feldspathic rocks and the feldspathic rocks are telescoped into the non-feldspathic rocks, overlapping them in silica content and obscuring any consistent trend that may exist in other components.

Actually there is a continuous increase in the number of atoms playing what might be called the silica role in the rocks as we pass from the peridotitic into the gabbroic rocks of the complex, if the dual role of aluminum is taken into account. By adding the molecular number of Al_2O_3 to that of SiO_2 half of the total number of aluminum atoms are assigned to the silica position, while by plotting the molecular ratio of Al_2O_3 against SiO_2 plus Al_2O_3, the variation of alumina playing the so-called "basic" role in accounted for. This is true because the total number of molecules of Al_2O_3 is just half of the total number of atoms of aluminum.

Figure 15, page 151, the variation diagram for the major components of the rocks, shows all 14 analyses plotted in the manner described. The major rock units forming the successive rings of the complex are dunite, augite dunite, wehrlite, olivine augitite, gabbro, and granulite. These rocks are designated in large capitals at the top of the diagram, and the points showing the values for these rocks are connected by heavy vertical lines. Analyses for minor rock types and variants of the complex include an augite dunite dike about four inches wide sharply cross-cutting olivine augitite, a wehrlite dike about two inches wide sharply cross-cutting dunite, the remarkable diopside-garnet dike rock given as specimen 390, item 103, table 1, page 29, a hornblendite dike considered to be an extreme variant of the beerbachite group given as specimen 99, item 112, table 1, page 29, a composite sample from several coarse dikes and masses of gabbroic pegmatite in olivine augitite, a hornblende gabbro porphyry from a dike several thousand feet from the complex cutting the country rocks and doubtfully included with the rocks of the complex, and the most alkalic and siliceous rock collected within the complex and apparently belonging to the sequence of rocks in the complex consisting of a vein or thin dike about an inch wide following a major joint set in olivine augitite near the outer part of the ring given as specimen 261, item 117, table 1, page 29. These minor variants of the complex are designated in lower case at the top of the diagram and the points showing values for these rocks are connected by thin vertical lines. The analysis for the andesite-basalt melaphyre is also given and designated by lower case. The points for this analysis are connected by a thin dashed line.

The major trend of chemical variation in the complex is established by the major rock units, therefore the solid lines showing the trend of variation for each of the major components are connected only to the points representing values for the major rocks. Thus it will be seen that the trend of variation in MgO

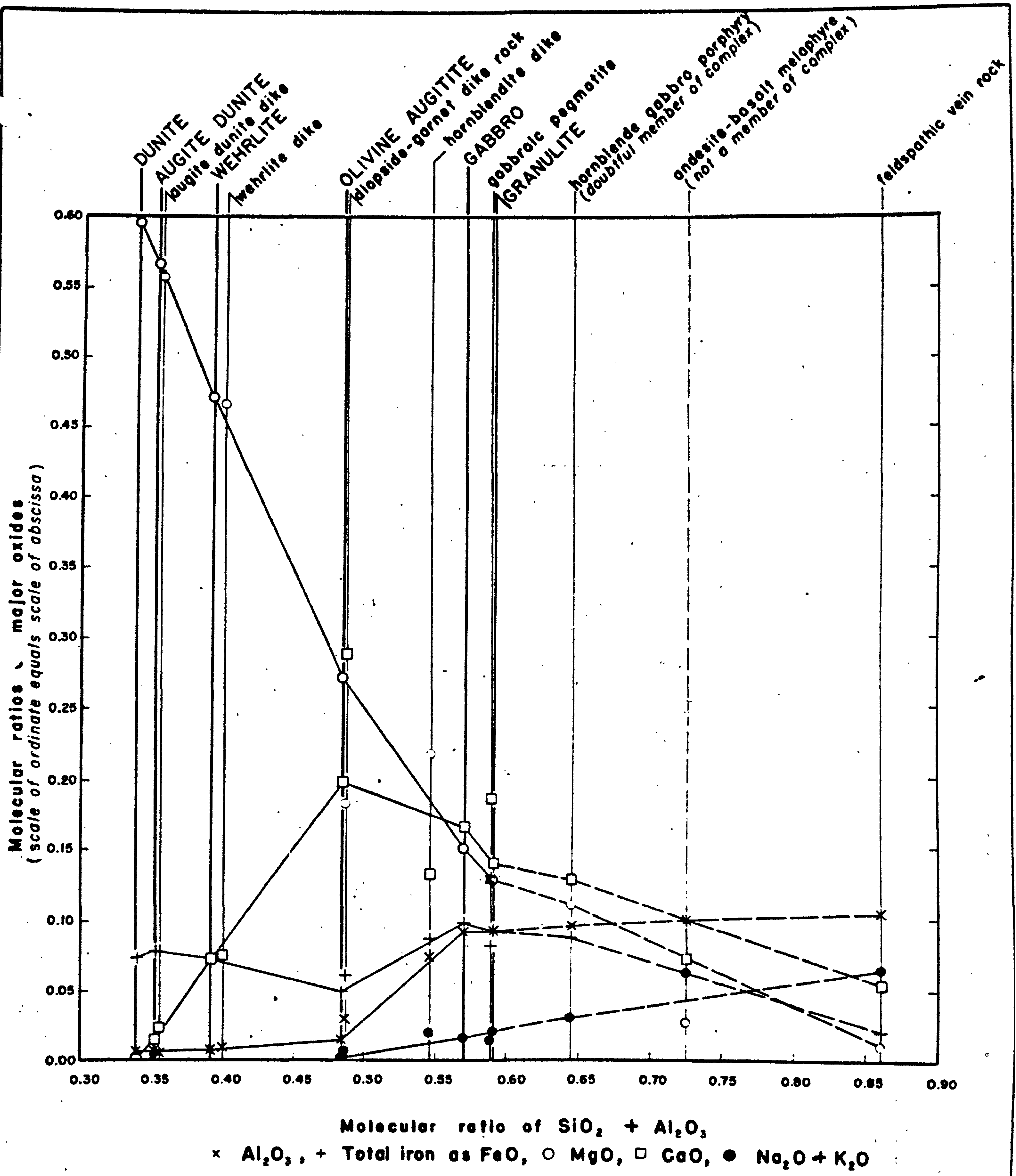

Figure 15, Variation diagram of major components of Blashke Island rocks.

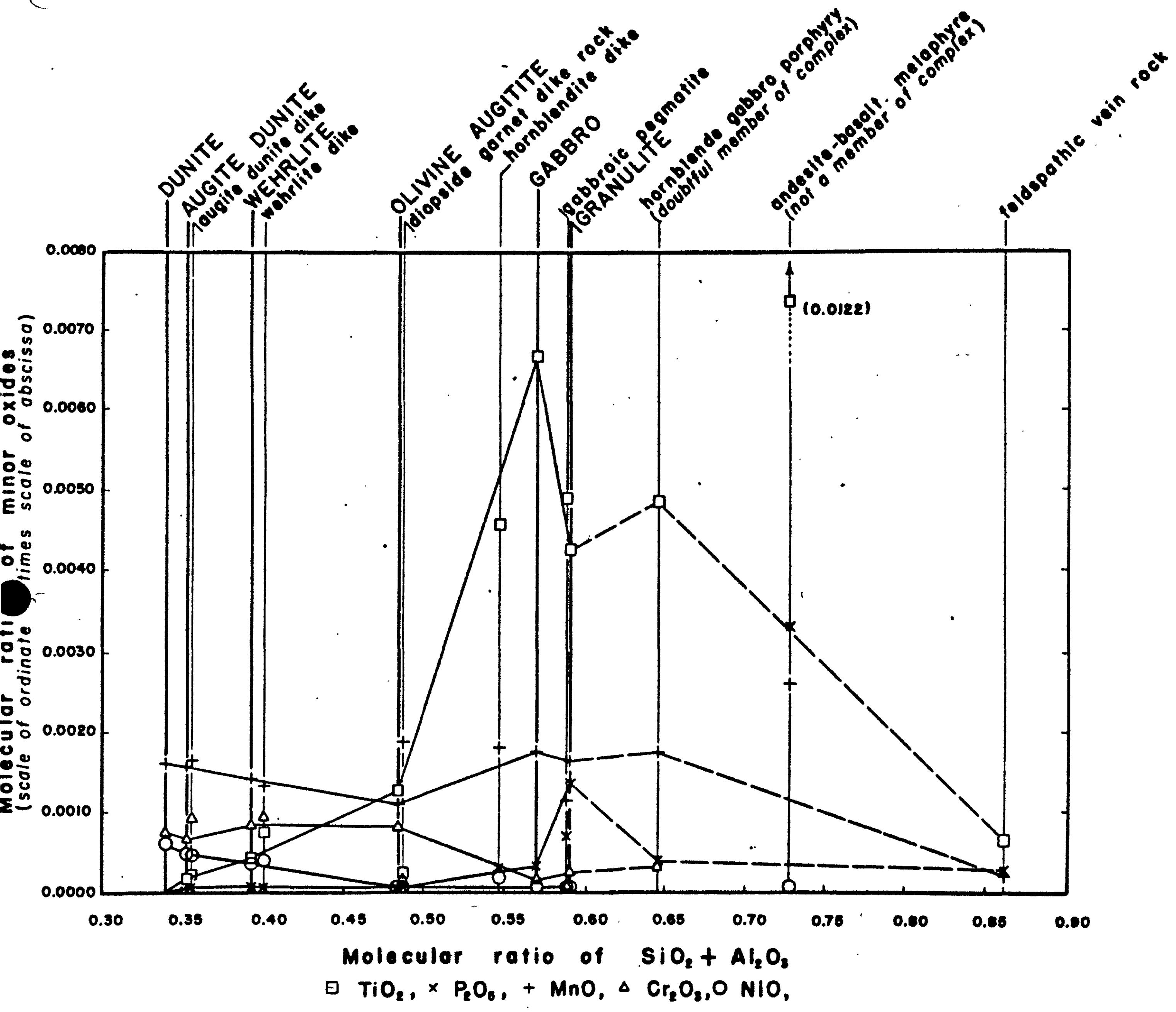

Figure 16, Variaton diagram of minor components of Blashke Island rocks.

steadily falls from dunite to granulite, and that the values for augite dunite and wehrlite dikes fall very close to this trend, but that the values for the diopside-garnet dike rock or the hornblendite dike do not fall at all close to the trend established by the major rocks. The trend of variation is continued by dashed lines from granulite to the hornblende-gabbro porphyry and the feldspathic vein rock, as they perhaps represent differentiates of the complex. On the other hand the values for the Tertiary andesite-basalt melaphyre obviously have no relation to the trends shown by the rocks of the complex, the value for lime falling quite by chance on the trend line for magnesia and that for alkalies on the trend for iron, while iron falls on the trend for alumina and only alumina shows any relation to the trends of the rocks belonging to the complex.

The strongest trend of variation shown by any of the major components is the trend shown by magnesia which drops steadily and very nearly on a smooth curve from dunite to the most siliceous and alkalic rock in the complex. Important deviations from the trend are shown only by the diopside-garnet dike rock in which calcium is abnormally high and magnesium abnormally low, virtually exchanging places with each other, and the hornblendite variant of the beerbachite group in which the reverse relationship is found with a drop in calcium content correlated with higher magnesium content.

Calcium increases linearly in the peridotites as magnesium falls owing to the substitution of augite for olivine as the major phase. However calcium reaches a maximum in olivine augitite and falls steadily thereafter. The decline in calcium is, of course, correlated with an increase in alkalies, mainly soda, owing to the increasing proportions of albite in plagioclase, which becomes the major phase.

The behavior of iron is particularly instructive. Unlike the other major components it remains relatively stable throughout most of the course of variation. The strong effect of the cryptic zoning in composition of olivine and augite is the main factor in stabilizing the role of iron. Olivine and augite are the principal iron-bearing minerals of the complex and both minerals become progressively richer in iron toward the periphery of the complex, but at the same time the minerals themselves become relatively less abundant so that the two trends compensate to some extent for each other. Other iron-bearing minerals such as hornblende, biotite, and ores play a part, but augite and olivine have the principal role. A more or less constant tenor of iron is thereby effective in progressively reducing the temperatures of crystallization of the major mafic phases from the center of the complex outward. Among the major rocks of the complex iron is at its lowest in the olivine augitite. A variation diagram of the major rock components based on Rosiwal analyses of the major rock units computed from the compositions of the mineral phases determined from optical data shows essentially the same relationships as the diagram based on chemical analyses. This calculation shows that the relatively low iron content of the olivine augitite is mainly due to the somewhat lower tenor of iron in the augite forming the bulk of the augitite ring as against the iron content of the olivine in the dunite. As long as augite is a major phase there may be some tendency for iron to vary reciprocally against calcium.

Alumina is an insignificant component of the peridotitic rocks. With the appearance of feldspar as a major phase it becomes a major component and shows little variation in the feldspathic rocks.

Three of the major components, magnesium, iron, and the alkalies show a more or less consistent trend across the diagram. The other two, aluminum and calcium show a sharp break in trend between the feldspathic and non-feldspathic rocks, calcium abruptly changing from a steep upward to a moderate downward trend, and aluminum changing from very low but slightly increasing values to relatively high and slightly increasing values. Chemically speaking, therefore, the major break in the complex lies between the peridotites, or truly ultrabasic rocks, and the gabbro. It is perhaps significant that the major physical discontinuity between rocks of the complex occurs between these two units. The existence of a zone of weakness along the contact between gabbro and olivine augitite and the lack of adequate exposures of this contact has been noted.

A variation diagram of the minor components of the Blashke Island rocks is given as figure 16, page 152. This diagram corresponds in arrangement to the diagram for the major components except that the scale of the ordinate showing molecular ratios of the minor components has been multiplied fifty times.

Chromium and nickel are mainly confined to the peridotitic rocks, with nickel closely correlated with magnesium doubtless due to its presence in small amounts in olivine, while chromium is relatively high in all the peridotites and is present chiefly in chromite in the olivine rocks and probably as a minor component of the relatively low-iron augite in olivine augitite. The role of chromium in augite has been discussed on page 79.

The close correspondence between the trend of manganese and that of iron obviously indicates that manganese occurs largely as a substitute for iron in a definite equilibrium ratio.

Phosphorus shows a distinct correlation with aluminum. It is a very low, almost constant, component of the peridotites, and is several times as abundant and, with an important exception, almost constant in the aluminous rocks. The exception is the granulite in which, as has been previously noted, the mineral apatite in coarse, anhedral grains is exceptionally abundant. This is true to a somewhat lesser extent in the gabbroic pegmatite.

The most remarkable variation is shown by titanium. In the peridotites it shows a strong correlation with calcium. With the appearance of aluminum in significant amounts, titanium increases markedly and is again more or less crudely correlated with calcium in the aluminous rocks, but at a much higher level. In other words, titanium shows a chemical affinity for calcium, but in much higher ratios in calcic rocks that are high in alumina. In view of the world wide association of ilmenite ores with anorthositic rocks this relationship may have broad significance.

Once a variation diagram has been constructed from a group of chemical analyses the question arises as to whether it means anything. Constructing a diagram involves taking a group of rock analyses and arranging them in a sequence based on the relative proportions of some important constituent. One should not be too surprised then to find the other components falling into some kind of logical order, even in a group of totally unrelated analyses chosen at random, because the other components are all to some extent functions of the component, such as silica, chosen as the basis for the diagram, and all rocks have to obey the same laws of physical chemistry.

Only when the sequence in which the analyses fall bears a very close relationship to actual sequences of rocks that are related to each other in the field can we assume that the variation diagram depicts a genuinely connected sequence of chemical variations. The variation diagram for the major rock units of the Blashke Island complex seems to meet this test. The major rocks fall in the variation diagram in the same sequence that they are met with in the field, both in regard to spatial relationships and sequence of formation. Among the minor variants there is less uniformity. The augite dunite and wehrlite dikes lie so close to the major rock types to which they bear the relationship of apophyses in the field that there can be little doubt that they are either derived directly from the major rock units or have formed by the same process as the major units. On the other hand, radical to significant departures from the trend of variation are shown by the diopside-garnet dike rock, the hornblendite dike, and the gabbroic pegmatite. Some special conditions must be invoked to explain their connection to the principal rock units. Nevertheless the minor rocks fall in proper sequence along the abscissa of the diagram.

It is obvious that the andesite-basalt melaphyre that has been correlated with an extensive group of Tertiary basaltic volcanics and dikes belongs to an entirely different sort of variation trend and probably is completely unrelated either directly or indirectly to the gabbroic rocks of the complex. This conclusion is, of course, supported by the field and petrographic evidence.

The chemical analyses have also been computed to von Wolff parameters and plotted on a von Wolff diagram in figure 17, page 158. The von Wolff diagram also brings out the sharp discontinuity between the peridotitic and the feldspathic parts of the sequence owing to the fact that one is essentially a non-aluminous sequence and the other aluminous. Where alumina appears as a major component, a corresponding percentage of calcium is subtracted from the chemical components used in computing the M, or melanocratic, value in the von Wolff system and added to the components making up the L, or leucocratic, value. Where alumina comes into the sequence abruptly, as it does in the Blashke Island complex, a sharp offset in the trend must appear in the von Wolff diagram, but an essential parallelism of trend is maintained. This is not to say that a suite of rocks cannot be collected in the Blashke Islands ranging gradationally from olivine-augitite with accessory plagioclase through melanocratic gabbros to the typical gabbro of the complex, but such a sequence would lie along the dashed line between augite-dunite and gabbro and constitute a sharp break in the direction of trend for both parts of the major sequence. An essential discontinuity in the complex between the peridotite and the gabbroic rocks is therefore not bridged by the existence locally of mineralogically transitional rocks between gabbro and olivine augitite.

The von Wolff diagram also brings out the consanguinuity of the augite dunite and wehrlite dikes with the major units of the complex, and the divergence from the major trend shown by the minor dike rocks.

The problem of origin of concentrically zoned ultrabasic complexes

The origin of ultrabasic rocks has been a lively source of controversy and invention down to the present and no attempt will be made in this paper to survey the voluminous literature or treat the subject in a general way. It is obvious at once that there are many kinds of ultrabasic rock masses not necessarily related in mode of origin. There are the great stratiform complexes with ultrabasic layers,

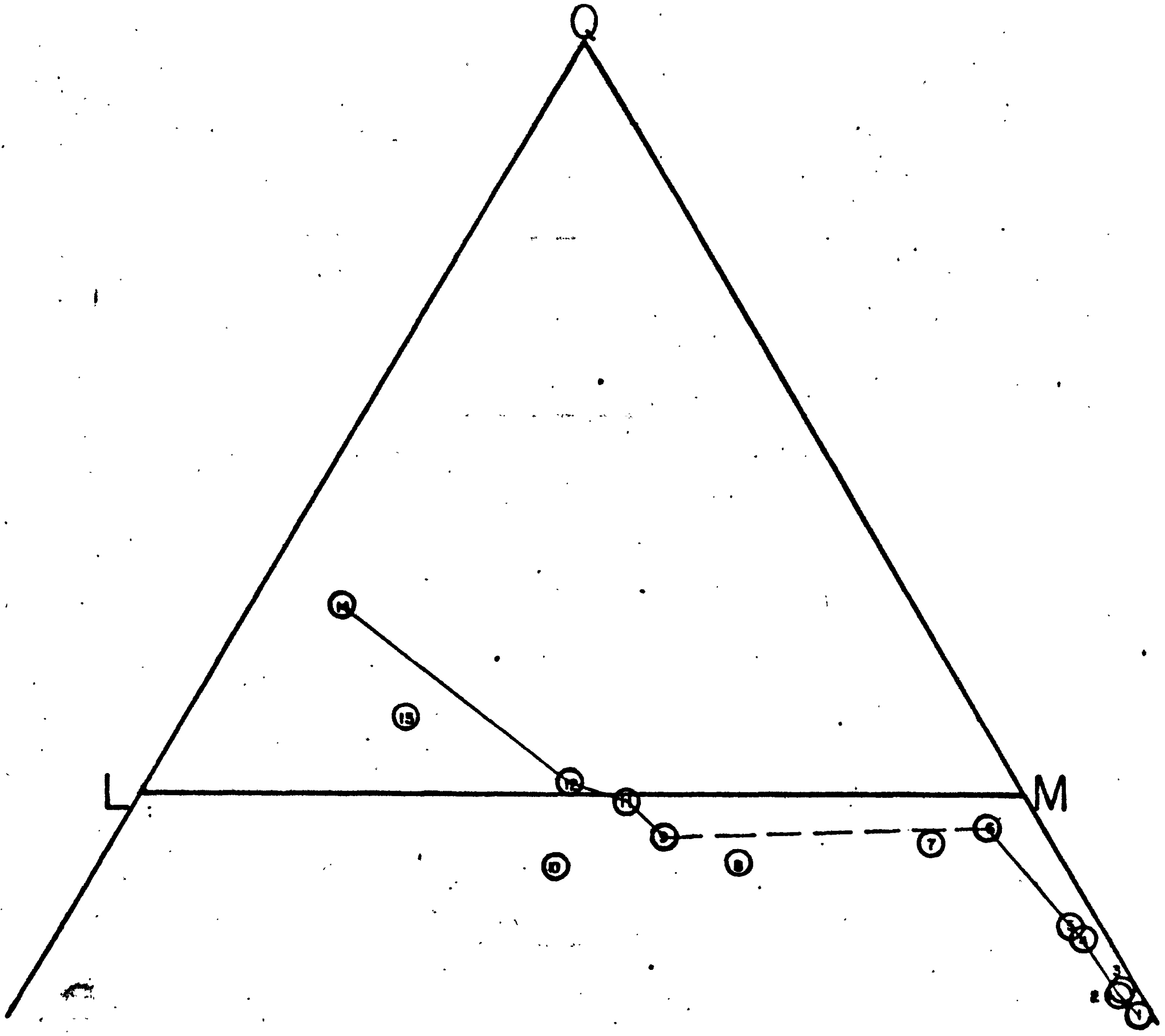

Figure 17, von Wolff diagram of analysed Blashke Island rocks.

Figure 17, Analyses plotted

Points joined by solid or dashed lines represent major rock units of the complex.

1. Dunite, composite specimen, column A, table 2.
2. Augite dunite, composite specimen, column B, table 2.
3. Augite dunite dikes cutting olivine augitite, composite specimen, column C, table 2.
4. Wehrlite, composite specimen, column D, table 2.
5. Wehrlite dikes cutting dunite, composite specimen, column E, table 2.
6. Augite dunite, composite specimen, column I, table 2.
7. Diopside-garnet dike rock cutting olivine augitite, specimen 390, column M, table 2.
8. Hornblendite dike of beerbachite group cutting olivine augitite, specimen 99, column P, table 2.
9. Gabbro, composite specimen, column U, table 2.
10. Gabbroic pegmatite dikes and irregular bodies in olivine augitite, composite specimen, column L, table 2.
11. Gabbroic granulite, composite specimen, column Y, table 2.
12. Hornblende porphyry dike cutting lower Silurian conglomerate and belonging to doleritic dikes older than the complex, specimen 453, column Z, table 2.
13. Andesite-basalt melophyre of Tertiary dike group, specimen 474, column ZZ, table 2.
14. Feldspathic vein rock occupying early formed flat lying joint in olivine augitite, specimen 261, column Q, table 2.

the serpentine intrusions, the isolated bodies of one kind of ultrabasic rock or another with or without strong contact effects on enclosing rocks, the concentrically zoned complexes, and various irregular and transitional types. In mode of emplacement, ultrabasic bodies range from sharply transgressive to fully concordant. They occur in regions where the tectonic setting ranges from intense deformation and metamorphism to relatively undeformed and unmetamorphosed. In explaining the origin of the Blashke Island complex we are concerned only with a concentrically zoned complex, but there may develop implications in regard to other ultrabasic and basic rocks.

Theories of origin have shown at least as great a diversity as the rocks themselves, and this is perhaps as it should be, except that there has been a tendency on the part of the theorists to extend their theories beyond the rocks to which they were applicable, thus encountering friction coming from other directions. At the present time several main lines of approach to the problem can be discerned. They fall into the following main groups:

1. Crystal fractionation of an ordinary basic magma with subsequent modification of the accumulated ultrabasic crystal fraction to fit the circumstances in which it is found.
2. Other kinds of differentiation of an ordinary basic magma with subsequent modifications to the ultrabasic fraction.
3. Cold or luke-warm intrusions of serpentine, olivine lubricated by serpentine, or olivine undergoing plastic deformation.
4. Various kinds of original ultrabasic magma, especially one approaching serpentine in composition.
5. Metasomatism.

In the author's view none of these general approaches have been applied to concentrically zoned ultrabasic complexes with notable success. However, much of the extensive Russian literature has been inaccessible, and it is in the Urals that many of the finest examples of this type of complex are found.

An interesting light on the problem of concentrically zoned ultrabasics is thrown by Duparc (Duparc and Grosset, 1916, pp. 226-227) whose conclusions regarding the origin of the Uralian complexes was stated as follows in 1916:

> "Il paraît incontestable que la différenciation s'est faite en donnant tout d'abord naissance aux gabbrox, aux norites, et aux roches subordonnées, ce qui a eu pour résultat la fixation de la presque totalité de l'alumine, des alcalis et d'une grand partie de la chaux. Le magma est ainsi devenu riche en fer et en magnésie et pauvre en alumine et en alcalis, condition favorable pour donner naissance aux pyroxénites par une nouvelle différenciation qui aura, comme contre-coup immédiat, la séparation de la koswite et des tilaïtes; la première, par addition au pyroxène et à l'olivine de la scorie ferrifère restée libre et qui entraîne avec elle une partie de l'alumine; la seconde, par fixation de restant de l'alumine et des traces d'alcalis, comme plagioclases basiques. Des lors le magma epuisé en sesquioxydes, est devenu essentiellement magnésien, la totalite de la chaux ayant en effet été fixée dans les pyroxènes et dans les feldspaths. Il se trouve ainsi dans des conditions favorables pour donner naissance à la séparation massive d'un sillicate ferro-magnésien, c'est-à-dire à de l'olivine compacte; c'est donc la dunite qui va dans ces conditions représenter le produit ultime de la différenciation magmatique. Il paraît hors de doute par l'examen fait sur le terrain, que ces différenciations successives sont concentriques, les gabbros à la périphérie et la dunite au centre. L'existance de chapeaux de pyroxénites sans racine, isolés à l'intérieur des massifs dunitiques a proximité immédiate de la ceinture pyroxénitique qui circonscrit ces derniers, en est une preuve évidente."

To modern readers this statement will appear naive in the extreme, reversing as it does the complete sequence of stability relations that has been established for rock-forming silicate assemblages. In fact it must have seemed so to many petrologists at the time it was written. But with it the present writer strikes one note of complete accord. The concentrically zoned ultrabasic complexes certainly <u>look</u> as if they had formed in the order suggested by Duparc. Therein lies the rub.

Camsell (1913, pp. 67-68), writing at about the same time as Duparc about a zoned complex in British Columbia, recognized the problem and foreshadowed certain aspects of a solution that will be developed in detail in later sections of this paper when he wrote:

> "The process does not appear to be simply a case of fractional crystallization and gravitative adjustment, because the stock should then show a separation along horizontal lines instead of, as it actually does, an acid shell around a basic core; but it appears rather to the author as if thermal convection currents had been set up in the magma chamber, and that, in the migration of the material around the chamber, certain minerals of the magma froze and separated out along the cooler walls. Such a process of separation is frequently made use of in chemistry and has been suggested by Becker as applicable also to igneous rocks. This process would

involve fractional crystallization to some extent, but the final effect would be that which now obtains in this stock, namely, a core of peridotite surrounded on the top and on all sides by a shell of pyroxenite. In the broader parts of the stock the top part of the shell has been eroded away, exposing the peridotite core, while in the narrow parts the pyroxenite cover still protects the peridotite core of the interior. To use a simple illustration the stock resembles a hard boiled egg, the peridotite being equivalent to the yolk, and the pyroxenite to the white of the egg.

The composition of the original magma was probably intermediate between that of the two principal types of rocks, and the small dykes which cut these rocks, and have such a composition, may represent portions of the undifferentiated magma injected into the cooling cracks of these rocks."

Modern readers familiar with the writings of Bowen (1915; Bowen and Schairer, 1933 , pp. 391-396) will quail at the readiness with which Camsell assumes a highly fluid peridotite magma and at the mechanism that he proposes, but the rock relationships that he describes put the problem squarely up to us.

Hypotheses of origin of the Blashke Island complex

A conscious effort has been made thus far to confine this report to facts and relationships observed in the field and determined in the laboratory. Such inferences as have been made have been of a limited and tentative nature and, at least in the author's mind, strongly supported by observed facts. The objective has been to build up as complete a picture as possible of the Blashke Island complex, colored as little as possible by pre-conceived ideas of how it ought to be.

No doubt a number of superficially applicable ideas for explaining the origin of the complex have already been effectively eliminated from serious consideration by the obvious implications of the observed facts. For example, the hypothesis of a cold intrusion is refuted at once by the strong thermal metamorphism around the contacts, but for the sake of completeness there are set forth below all of the general kinds of hypotheses that have occured to the author as possibly explaining the origin of the complex, though some are admittedly far fetched on the face of it. This listing of general kinds of possible explanations begins with purely mechanical and structural schemes, followed by ideas involving both structural and chemical processes, and concluding with hypotheses that are largely chemical. Naturally most of these hypotheses are derived from ideas current in geologic literature. An attempt will then be made to eliminate those that can be shown to be untenable and develop in detail an hypothesis that the present author frankly favors.

1. The complex was emplaced as a solid mass of serpentine or plastically deformed olivine.

2. The complex represents a sequence of separate intrusions having a ring dike pattern. The successive intrusions may be entirely unrelated or related only in a broad, general way to a regional cycle of petrogenesis.

3. The complex is a sequence of ring dikes and a core. The successive rock units were derived by differentiation at a lower level of a single or complex source-magma and injected in the sequence in which they were derived.

4. The complex formed by differentiation of a magma in an entirely different pattern, say as a stratiform sheet, and was subsequently deformed by acute doming into its apparently concentric configuration at the level at which it is exposed.

5. The complex is a cross-section of a lower level of a vertically extended magma column, perhaps terminating in a volcanic rock. Differentiation of one kind or another resulted in the rising of salic fractions of the magma and the sinking of mafic fractions which by virtue of the convection pattern set up, collected in a concentric configuration near the base of the column. Other cross-sections at other levels in the column would reveal different rock types and perhaps different patterns.

6. The complex formed entirely by recrystallization and metasomatism of country rocks acted on by some energetic agency diffusing outward from a central source or inward toward a center.

7. The complex formed from a mass of magma that was intruded into its present position and formed concentric shells through some method of differentiation that may have included sequential crystallization, vigorous reaction with enclosing rock, and extensive differential diffusion of various components along strong temperature and concentration gradients. The magma was very hot but was

not necessarily entirely liquid. It may have been a polyphase magma consisting of a mixture of crystals and one or more fluids.

1. Solid intrusion

This hypothesis may have some acceptance because it seems to explain certain serpentine masses, but it breaks down completely in the Blashke Islands. Strong reasons for rejecting any deformation after serpentinization have been given (p. 77), and even if we admit that an olivine mass may be peculiarly adaptable to plastic deformation before serpentinization, we must still account for the massive, coarse-grained, pyroxenite ring with its completely unsheared and ungranulated allotriomorphic fabric. The many minor irregularities, the gradational contacts between dunite and pyroxenite, and the gabbro ring are stumbling blocks to this idea.

2. Separate unrelated magmatic intrusions

This hypothesis may be rejected almost summarily. From the regional point of view it fails to explain the close association in a few well-defined isolated complexes with a systematic concentric structure of the dunite-pyroxenite-gabbro sequence without the random development elsewhere in the region of independent dunite and pyroxenite masses with different associations. It involves the creation of two highly specialized magmas, one pyroxenitic and the other dunitic, capable of independent intrusions. It can be made to fit the pattern of cryptic zoning and systematic chemical and mineralogical variation shown by the complex only by assuming a complicated sequence of interaction and mutual contamination between the successive intrusions. The overall petrologic, mineralogical, chemical, and structural unity of the complex belies such an adventitious origin.

3. Ring dike sequence differentiated at depth

The original magma in the Blashke Island complex can have been no less mafic than a strongly undersaturated gabbro, for from it substantial ultrabasic fractions must be derived leaving a normal saturated gabbro as the most acid fraction of any quantitative importance. Before injection took place a substantial part of the differentiation must have taken place in the magma chamber because the gabbro ring is largely composed of saturated or only slightly undersaturated gabbro. Cauldron subsidence as a ring fracture of a block of country rock must then have ensued with the upwelling of the gabbroic fraction. The mechanism seems feasible up to this point, but here it meets fatal difficulties. From this point on, the subsiding block must displace first pyroxenite and then dunite, for presumably these later fractions of the magma differentiated by fractional crystallization and existed in the magma chamber as dense mushes of solid crystals. Otherwise a method of differentiation must be devised that can produce liquid fractions of relatively pure dunitic and pyroxenitic composition. It would be beating a dead horse to push the ring dike hypothesis any further.

The ring dike mechanism is independent of active intrusive pressure and depends on upward displacement of magma by subsidence of a crustal block into the magma chamber (Richey, Thomas, and others, 1930, pp. 58, 59). A somewhat more convincing hypothesis along the lines of a ring intrusion differentiated at depth can be made out if the passive mechanism is abandoned and it is assumed that the gabbro was intruded as a plug into the enclosing rocks, that this plug partially solidified around the margins, and that the still plastic core of the plug served as the avenue of least resistance for the forcible intrusion of pyroxenite followed by a dunite intrusion into the core of the pyroxenite. This is essentially the hypothesis offered by Adams (1903, pp. 281-282) to explain the concentric arrangement of rock type in the Mount Johnson intrusive of the Monteregian Hills.

The major difficulty with this modification of the ring dike hypothesis as applied to an ultrabasic complex lies in the nature of the supposed pyroxenitic and dunitic differentiates. It was pointed out above that both ultrabasic fractions had to be either largely solid crystals or else liquid differentiates, for which no possible mode of origin can be imagined, at least the writer can imagine none. No evidence is seen in the fabric of either the massive dunite or the pyroxenite in the Blashke Island complex for intrusion after being fully differentiated and almost completely solid. There may be ways of getting around this difficulty in the case of dunite as has been suggested by Bowen and Tuttle (1949, p. 455), but the coarse, allotriomorphic-granular, unstrained and unsheared fabric typical of the olivine augitite in the Blashke Island complex appears to eliminate solid intrusion or even semi-solid intrusion as a method of emplacement for the pyroxenitic rocks. The successive intrusion of a differentiated sequence falls down on this score alone, but numerous difficulties involving cryptic zoning, partially gradational to gradational contacts, and interdiking of rock units are also present. The assumption that cryptic zoning and gradational contacts could be explained by reaction and assimilation between the successive intrusions is untenable if they are differentiates of an original magma because as such they are presumably already close to equilibrium with each other and no longer strongly reactive.

4. Doming of a stratiform sheet

This hypothesis can be summarily dismissed on the grounds that the complex shows no evidence at all of intense deformation subsequent to its formation. The thickness of the rock units involved as compared with the dimensions of the complex would require very strong deformation to achieve the present configuration from originally flat-lying strata.

5. Differentiating magma column

Masses of dunite, wehrlite, and interbanded dunite and augitite are present as inclusions in lava and ejectamenta from basaltic volcanoes (Macdonald, 1949, p. 1553) indicating that such rocks do form in volcanic conduits, although there is no evidence that they form in large bodies or concentric complexes. If a magma is undergoing differentiation by fractional crystallization in a volcanic conduit along the lines described by Bowen (1928, pp. 159-168) we may expect the early formation of olivine crystals in the liquid and their sinking to form accumulations of olivine in the lower part of the conduit. The examples given by Macdonald in the reference cited above show that these accumulations can aggregate and form masses with the allotriomorphic granular texture characteristic near the core and exhibits strong flow structures owing to the convective circulation it underwent.

Some of the concentrically zoned peridotite complexes in the Urals (Duparc and Grosset, 1916, plate I) are isolated bodies enclosed here and there in masses of gabbro of batholithic proportions. It might be imagined that these bodies represent heaps of olivine crystals superceded by augite or an orthopyroxene that collected beneath places where the gabbro mass extended upward for a considerable distance or reached the surface in volcanic vents. Olivine would crystallize in the higher parts of the column and pile up below. Eventually the supply of olivine would be exhausted and pyroxene would settle out and mantle the pile of olivine, which by a process of partial melting and giving up of a little fayalite may be supposed to have sintered into a steep-walled, solid mass rather than slumping out over the floor of the chamber. Finally the entire gabbro mass would crystallize around it, but it is difficult to see why the great mass of gabbro should be cryptically zoned and purged of normative olivine beyond the immediate vicinity of the peridotite without a process of convective circulation and return of olivine-free magma to the chamber below.

The hypothesis outlined above has the typically unconvincing air of most geological schemes that extend far beyond observable facts and seem to require an excessive amount of what might be styled "subterranean plumbing," but it may be some consolation to those who see crystal settling as the only feasible method of quantitative magmatic differentiation and basaltic magma as the only raw material. Among the problems that it does not solve is that locally the peridotite in the Blashke Islands is in direct contact with country rocks and here the country rocks have undergone a higher degree of thermal metamorphism than where they are in contact with gabbro. Furthermore the process has to operate near the bottom of a long magma column, where presumably all the rocks for considerable distances around were raised to high temperatures, not just a zone a few hundred feet wide. The intrusive relations of the marginal facies of the dunite core toward both the dunite and the pyroxenite are not accounted for. The many large and small irregularities in the dunite-olivine augitite contact are not accounted for. It is difficult to believe that such a process could result in such a high degree of monomineralic segregation. The amount of gabbro in the Blashke Island complex is disproportionately small. For the mechanism as outlined to be effective a convective cell of adequate dimensions must exist, so that right down to the completion of the process the central core of accretionary dunite and pyroxenite should be surrounded by a substantial ring of circulating gabbroic magma. Gabbro is very irregularly distributed and locally present in a very thin zone or missing around the northern and western margins of the Blashke Island complex. We should expect these complexes only in the deeper zones of gabbroic magma chambers and not in narrow necks cutting sharply through low-grade metamorphic rocks. Where a mechanism of crystal settling and convection has been well established as the effective process of differentiation in a basaltic magma, of which the Skaergaard intrusion (Wager and Deer, 1939b) is perhaps the finest example that has been worked out in detail, the result is a stratiform complex, as would logically be expected.

Wahl (1946, pp. 417-441) has recently advocated a mechanism of thermal diffusion and convection as a means of differentiating magmas under thermal gradients based on new experimental evidence of the effectiveness of the process. The process as outlined by Wahl is most effective in tall columns of liquids or gases with restricted cross-sections. Wahl cites numerous experiments on solutions and mixtures of gases that have resulted in the development of opposite ends of the elongated chamber containing the solution or gaseous mixture of separate fractions with strongly contrasting concentrations of various ions, atoms, or molecules. This differentiation of the liquid or gas is caused by a strong temperature gradient from the core of a long, narrow tube outward or from one wall of narrow elongated chamber to the other. The temperature gradient causes differential diffusion of components and this results in density differences that start convective circulation within the system. Wahl has suggested applications of the mechanism to a number of differentiated rock complexes, including several that have a concentric zonal arrangement of rocks analogous to the Blashke Island complex.

The rock complexes cited by Wahl that have certain points of similarity with the Blashke Island complex are: Mount Johnson, Monteregian Hills, Canada; Almunge, central Sweden; Norra Kärr, southern part of central Sweden; and Magnet Cove, Arkansas (Wahl, 1946, pp. 430-440). All of these bodies are relatively steep-sided and more or less cylindrical in form and have a zonal arrangement of rocks with basic cores and alkalic outer zones. Chemically there is considerable difference between these complexes and the Blashke Island complex in that they mainly show an enrichment in alumina and soda outward and lime and magnesia inward. Soda plays a subordinate role in the Blashke Island complex, alumina is virtually absent from the two major inner zones, and within these zones lime increases as magnesia decreases.

There is one point about Wahl's application of thermal diffusion and convection to concentrically zoned complexes that, on the face of it, is not consistent with the experiments cited as exemplifying the process. The experiments, if this author understands them correctly, involve setting up a temperature gradient from the axis to the walls of a tube containing a fluid solution or mixture. Under the influence of the temperature gradient a relative concentration gradient from the center outward is set up between the components, depending on their different rates of thermal diffusion. At the same time a convection will be set up, the fluid along the walls of the column sinking if its density has increased due to thermal contraction or enrichment in a heavy component, or rising if it has been sufficiently enriched in a lighter component, while the fluid in the center of the column will move in the opposite direction. In this way the fluid will become progressively enriched in one component at one end of the tube and in the other component at the other end of the tube through a continuous cyclic circulation until an equilibrium is reached. At this point the <u>bottom</u> of the tube will contain a high concentration of one component and the top will contain a high concentration of the other, but the concentration gradient in either component from the core outward at any given level in the tube will at all times depend only on the differential rates of thermal diffusion and no concentric zonal concentrations of one component over the other can be expected in the system beyond that produced by simple thermal diffusion.

If the above analysis is correct, Wahl may have pointed out a very effective way in which magmas may differentiate into different fluid fractions at different levels in a magma chamber, but without modification it appears no more effective than simple thermal diffusion alone in producing concentric zonal distribution of rock types. However, Wahl points out at the beginning of his paper (Wahl, 1946, pp. 417-420) new experimental evidence and other reasons for believing that simple thermal diffusion may be far more effective than has been generally believed by many petrologists.

In view of the inadequacy of some of the more conventional explanations, the process of thermal diffusion and convection proposed by Wahl offers a welcome new approach to the problem of the concentric zonal arrangement of rock types, and until it has been applied experimentally to solutions more nearly approaching rock magmas we are not entitled to say on a priori grounds what its effects are likely to be. For one thing, the thermal diffusion and convection system set up in rock magmas would certainly be modified by the onset of fractional crystallization and the introduction of solid phases into the convection system. It would also be modified by reaction with enclosing rocks.

6. Metasomatism

The author does not feel fully enough at home in the finer points of "transformist" doctrine to even be sure that proponents of this process would claim such an origin for a complex such as the Blashke Island, but Reynolds (1943, p.236) has advocated replacement of country rock for the genesis of biotite peridotite and biotite pyroxenite and a suite of associated basic rocks, and Lacroix (1941, pp. 261-265) has shown that a narrow band of rock rich in forsteritic olivine enclosed in a biotite pyroxenite probably formed by pneumatolitic action. In the Newry complex described by Reynolds the peridotites are associated with a large mass of granodiorite and in Reynolds' view have formed by the localization of iron, magnesium, and calcium ions in a so-called "basic front" advancing ahead of a wave of sodium, calcium, and silicon atoms that produced the granodiorite.

It is true that the entire region of southeastern Alaska abounds with diorite, quartz diorite and granodiorite intrusions. In fact it contains part of one of the largest of such masses known - the Coast Range batholith, but there are no exposed masses of any size nearer than 12 miles from the Blashke Islands, though admittedly the waters of Clarence Strait could conceal other bodies of considerable size and any amount of it may lie beneath the present surface. However, the country rocks of the Blashke Islands and all the neighboring islands give no evidence for the proximity of a large intrusion with attendant aureole, unless the Blashke Island complex per se is taken for such evidence. Therefore the author finds it hard to imagine how such intense and sharply defined localization of material undergoing diffusion is possible without a tangible localized source and will make no attempt to apply the transformist concept to an explanation of the details of the complex. Accusare nemo se debet.

7. Differentiation in place of a polyphase ultrabasic magma, the hypothesis of origin advocated by the author

If the Blashke Island complex differentiated in place from an intrusive body of magma, and if the complex and enclosing rocks are assumed to contain fixed within them the major part of the rock-forming components with which the original magma was endowed, the magma must have been much more magnesian and sub-silicic than any ordinary undersaturated gabbro. In fact it must have approximated a wehrlite, and it is an interesting fact that at the only place in the Blashke

Islands where an absolutely sharp contact between peridotite and rocks that can be unequivocally identified as granulitized country rock can be observed, the peridotite is a slightly feldspathic wehrlite (specimens 361, 362, and 365, items 89, 88, and 87, table 1). It is not absolutely necessary to assume that the complex has not lost upward and beyond observation a substantial less basic fraction. In the area described by Camsell (1913, pp. 74-75) a sizeable body of augite syenite is contiguous with the ultrabasic and locally passes into a gabbroic facies that grades marginally into the pyroxenite shell of the complex, although Camsell himself considered most of the syenite to be definitely younger than the ultrabasic mass. In the Uralian examples mentioned above some of the ultrabasic bodies are surrounded by voluminous gabbro masses. However the field relations in the Blashke Island complex and in the other southeastern Alaska peridotite complexes give no direct hint that the complexes are connected with proportionately large, less basic differentiates. In the argument presented below a relatively large amount of gabbro or other less basic rock is more difficult to explain than a small amount, granting the assumptions on which the argument is based.

If the anhydrous composition of an original magma were something intermediate between dunite and pyroxenite, approaching a wehrlite, several questions arise as to the state of the magma. In regard to temperature we are entitled to assume that the magma was near the upper limit of magmatic temperatures during the intrusion of the Blashke Island complex. Country rocks of low metamorphic rank have been converted by contact with the complex into gabbroic granulite of very high metamorphic rank. Many of these granulites are fully comparable to the granulites representing the highest grade of thermal metamorphism attained in the celebrated Tertiary igneous complexes of western Scotland (MacGregor,1931, pp. 506-521). Early estimates of magmatic temperatures of the gabbroic magma at Mull were in the neighborhood of 1,400°C (Thomas, 1922, pp. 229-260), and the geologic evidence at Mull pointed to this temperature having been attained at depth, not due to near-surface phenomena to which some determinations of high volcanic temperatures have been attributed.

This estimate was based on the supposed stability relations of sillimanite. Subsequently, Bowen (Bowen, Grieg, and Zies, 1924) showed that the mineral taken for sillimanite was actually a new mineral, mullite, and synthesized it in melts at temperatures as low as 1050°C. (Bowen and Grieg, 1924) so the evidence at Mull is inconclusive. Measurements of the temperature of basaltic lava have ranged well above 1,000°C. but some of the higher measurements have been attributed to gas reactions at the surface (Jaggar, 1917). However, Zies (1946) has recently shown that the lava emitted from Paricutin is probably at least 1,200°C. and shown that gas reactions are not responsible for this temperature. The present writer is inclined to accept Zies' estimate as a minimum for the upper limit of temperature in hot basic magmas and suggests that a peridotite magma could be expected to range substantially higher where evidence for high temperature contact effects is present, as in the Blashke Islands.

Present experimental data do not entitle us to say what the state of a wehrlite magma under a vapor pressure of water appropriate to considerable depth in the crust would be at a temperature 300°C. or more above 1,000°C. Bowen and Tuttle (1949, pp. 439-460) have shown that no liquid phase exists in a system containing natural olivines with about 10 percent fayalite and water at a pressure of 15,000 lbs./in.^{2}, equivalent to a depth of more than 2 miles in the crust, and a temperature of 1,000°C. Several hundred degrees above this temperature, at much higher pressures, and with the addition of a good deal of lime, several additional percent of silica anc iron oxide, and small amounts of other minor components including other volatiles such as CO_2, we can only speculate as to the state of the magma.

It is not unlikely that the elevation of temperature and pressure, and the addition of other components less refractory than MgO would result in the melting of some, or possibly all, of the olivine and the appearance of a liquid silicate phase rich in dissolved volatiles. Some highly magnesian olivine might remain as a solid phase in equilibrium with the liquid fraction. Another fraction of the magma might exist as an aqueous gas phase. If a gas phase were present it would be at a temperature and pressure far above the critical values for water, its most abundant component, and would approach an aqueous solution in density and in concentration of non-volatile solutes (Morey, 1942) (Kennedy, 1950). If the gas phase were not actually present in the magma it might be potentially present and escape from the magma where the enclosing rocks were permeable to gaseous emantions, as suggested by Ingerson (1934). It is also possible that the crystallization of the anhydrous silicates, olivine and augite, at relatively high temperatures along with the lack of alkalies and excess silica in the original magma would result in the retrograde formation of a supercritical gas phase after crystallization had progressed to some degree. The magma is thus envisiaged as a hot, mobile mixture or emulsion of two or more phases. It is possible that a supercritical gas phase, if not present initially, would come into existance where the surrounding rocks are permeable to chemically active gaseous solutions under high pressure, or as the result of crystallization at high temperature of anhydrous minerals, or with the release of pressure as the magma ascends into higher levels.

The actual or potential existence of a gas phase may also supply the motive power for the intrusion of the magma. The author has shown that some clastic dikes are injected by a mechanism of elastic response to the opening of avenues of weakness where the interstices of the clastic material are occupied by a compressed gas such as steam or natural gas (Walton, and O'Sullivan, 1950).

The injection of a hot ultrabasic magma into cold country rocks of quite different composition must set up powerful temperature, concentration, and vapor pressure gradients. Under the impetus of these strong gradients a vigorous reaction between country rocks and magma may be anticipated, with consequent modifications to both. Is it reasonable to believe that the kind of changes that would take place could produce the Blashke Island complex?

Certainly the modifications to the country rock are far from hypothetical. Low grade chloritic rocks containing abundant quartz and alkali feldspar have been converted into granulite of gabbroic composition. The geologists dealing with the granulite associated with the Tertiary igneous complexes of western Scotland have generally held the view that these granulites are produced by the thermal recrystallization of basaltic lavas (Harker, 1904; Thomas, H.H., Bailey, E.B., and others, 1924; MacGregor, A.G., 1931) through which the intrusions pass. Thus little change in composition during metamorphism need be assumed. In the Blashke Islands a variety of rocks including laminated argillites and graywackes, conglomerates, and volcanics have been converted into granulite. Mineralogical differences have been shown to exist between the metamorphosed facies of these rocks (pp. 52-58), but all of them have achieved a mineral assemblage approximating gabbro. The detailed analyses necessary to fully demonstrate the point have not been made, but it seems apparent that considerable changes in composition must have taken place in some of these rocks to bring them to gabbroic granulite. Similar transformations have been convincingly demonstrated by Grout (1933), who has shown that slates are converted to granulites approaching gabbro in composition and mineralogy near contacts with the Duluth gabbro. It is further suggested that the conversion to granulite is only a part of the story and that where the country rocks were open to an accession of volatiles, as along fractures and in more permeable beds, recrystallization has advanced to the point where these rocks fully resemble gabbro. This origin is particularly advocated for the highly irregular gabbroic rock commonly containing some hypersthene and biotite around the western rim of the complex. It is also suggested that by an intensification of this process in especially favorable places, partial or complete fusion and solution has taken place to produce a fully mobile gabbroic magma out of gabbroized country rock. The gabbro ring and nearby related bodies of gabbro are accounted for in this way.

Sosman (1950, p. 77) has recently pointed out that magmas unsaturated with water will absorb water from surrounding rocks causing a movement of fluids along a falling pressure and concentration gradient toward the center of the unsaturated magma. There is no direct way of knowing if a magma such as that proposed here would be saturated or unsaturated with water. It is generally assumed that igneous magmas are just saturated or nearly saturated with volatiles where they originate, and the presence of the volatiles is appealed to to explain their fluidity. When they are intruded into higher levels with lower confining pressure and the crystallization of anhydrous phases begins, it is thought that the relative vapor pressure of the volatiles in the magma increases and that there is an outward migration of volatile emanations, mainly water. If an ultrabasic magma must be undersaturated with water and the situation is reversed, as Sosman suggests may be the case, so that the migration of volatiles is inward rather than outward, we may sill envisiage the extreme gabbroization of the more permeable rocks surrounding the complex, culminating in the creation of gabbroic magma, fluxed by incoming rather than outgoing water. The other effects suggested here as dependent on a fluid concentration gradient set up by an outward migration of fluids from a fluid-saturated magma, might also be produced by an inward migration of externally derived water. Of course the question is not merely hypothetical if the process of differentiation outlined here were actually operative. One condition or the other must have actually existed. However in the present state of knowledge, or perhaps one should say ignorance, it is not possible to answer the question on the basis of direct evidence. Both alternatives may be entertained, but the author is inclined to believe that a magma capable of emanating fluids is the more probable.

In order to convert country rocks into gabbro considerable changes must take place in the ultrabasic magma. It must lose heat, and in so doing crystallize. Silica and the alkalies must be driven out of the country rocks and calcium and magnesium added so that a chemical interchange must take place between the country rock and the magma. This interchange probably takes place by thermal diffusion and also by the transport of materials in solution due to movement of fluids along vapor pressure gradients. One medium for diffusion might possibly be a supercritical fluid phase, mainly water, emanated by the magma and permeating all the rock to some degree.

The question of the efficiency of diffusion in liquid magma has been touched on in the discussion of Wahl's ideas on thermal diffusion and convection. His contention that it has been gravely underestimated has been cited on pages 170 and 171. Much new experimental work in this field is unpublished, but we get strong hints as to its effectiveness from such statements as the following: "At the laboratory there was developed a liquid thermal diffusion process for separation of uranium isotopes." (King, E.J., 1945, p. 42).

Thermal diffusion in a supercritical vapor phase of high density is another matter. Experimental verification of the reality and a hint as to the possible quantitative importance of this process is given as an interesting sidelight to the paper by Bowen and Tuttle (1949, pp. 441 and 459-460). Appreciable vapor transport of silica and iron in a matter of a few hours time are shown to have taken place, but Bowen and Tuttle make what seems to this author to be an unnecessary assumption in regard to the mechanism of the effects observed by them. They state:

> "It was found that convective circulation of water vapor took place in the pressure chamber and in the tube connecting it with the pump, even when the bore of this tube for a considerable distance from the pressure chamber was reduced to capillary size. As a result of this circulation SiO_2 was abstracted from the charge and deposited elsewhere in the apparatus, and a definite change of composition of the charge resulted, in spite of the fact that the solubility of SiO_2 in the vapor is excessively small. Moreover some iron oxide was at times similarly transferred to the charge from the steel parts of the apparatus. To reduce these effects the small platinum crucible was covered with another crucible inverted over it and telescoping with it in a very snug fit. Even with this arrangement transport of material to and from the charge was not entirely eliminated."

(Bowen, N.L. and Tuttle, O.F., 1949, p. 441).

Convective circulation in capillary tubes and around inter-locking crucibles can hardly have been effective. The experiment seems to prove that the transport of SiO_2 and iron took place by diffusion in the supercritical vapor phase. Moreover, it is to be noted that it was iron that was transported, not iron oxide. The steel walls of a bomb can yield up only atoms or ions of iron and oxidation must have taken place by reduction of water in accordance with the equilibrium relations that have already been discussed on page 127 in connection with oxidation of iron during serpentinization. If iron oxide had been available as the raw material much more spectacular effects might have been achieved, because a corresponding oxidation of hydrogen could have taken place preventing the attainment of an equilibrium. In the case of silica it may be silicon that is transported in one direction and hydrogen in the other with corresponding oxidations at both ends of the system. The question of whether it is convection or diffusion that took place is important because if it were diffusion it means that effective supercritical or vapor phase transport is largely independent of the motion of the fluid and the concentration of the transported substance in the vapor phase. If the effects depended on the streaming of the supercritical fluid or vapor, the low concentrations of most rock-forming components that have been shown to be soluble in supercritical water vapor would require veritable oceans of water to produce large scale effects (Kennedy, 1950). The same thing is true to a somewhat lesser degree of the hydrothermal solutions that figure so prominently in geologic schemes. The large-scale transportation of materials inferred in contact metamorphism and commonly attributed to pneumatolytic action bear eloquent testimony that there is an effective process. Bowen's experiment suggests that it is one of diffusion. Silica is yielded up to the supercritical solvent in one part of the system and removed from the solvent in another. This is experimental fact, not theory. If they get to the point of removal from the point of supply by diffusion, the actual concentration of silica in the fluid at any one time may never be large, in fact it may at all times be minute, but if the atoms diffuse through the fluid at a rapid rate a large quantity of substance can pass through the fluid in low concentrations.

The rate of diffusion may be by far the more important factor, for it seems reasonable to suppose that the rate of diffusion in dilute supercritical solutions is relatively rapid, at least by geologic standards of rapidity.

Supercritical water vapor has a small, but appreciable, solvent power for pure silica. It has been shown by Kennedy (1950) that this solvent power is a function of temperature and specific volume and continues to increase with temperature as water passes from the liquid to the supercritical gaseous state, providing the pressure is sufficient to prevent an abrupt change in specific volume as the critical temperature is passed. In some more complex silicate solutions the solvent power of supercritical water vapor may be very great. Morey (1942, p. 987) states that some experimental results indicate over 50 percent solid material in solution in supercritical water vapor for some composition ranges in the system, Na_2O-SiO_2-H_2O. If appreciable amounts of non-volatile solutes are present in a supercritical vapor phase, it seems reasonable to suppose that rates of diffusion would be relatively rapid owing to the high temperature and low viscosity of the medium.

However the differential transfer of components need not take place entirely by diffusion. If a gas phase containing non-volatile material in solution is being emanated and is permeating the surrounding rocks, we may expect that certain components of the magma are more soluble in the gas phase than others and these will be carried outward into the surrounding rocks to react with them and change their composition. The magma is thus improverished in some components and relatively enriched in other components that form early solid phases or remain in a liquid phase with less penetrative power for the surrounding rocks. The liquid phase of the magma may also increase in concentration toward the outer parts of the magma body owing to the strong temperature gradient between magma and country rock. Cooling of the outer part of the magma will cause an increase in density and lowering of vapor pressure of the liquid phase and liquid will move outward from the hotter interior where the vapor pressure is higher to balance this loss of volume. Thus the density and concentration of the liquid phase will be greater toward the margins, and the core will be enriched in those components present in the high-temperature solid phase or phases.

In the presence of an aureole of saturated fluid at high vapor pressure, the strong temperature and concentration gradients between magma and country rock may be expected to result in the differential movement of components of both the country rock and magma by diffusion and by bulk movement of the fluid phases. At the same time, owing to the same gradients, different stability relations are set up in different parts of the system so that different solid phases may be expected to be stable in different places. The writer is not competent to adequately analyse from the physical and chemical standpoint the effects to be expected in the system, and indeed, much of the fundamental data for such an analysis is as yet unknown. The writer can, however, outline what the effects would have to be in order to produce the Blashke Island complex, point out a few reasons for deeming these effects possible, and hope that in time the physical chemist can make the final evaluation.

Within the magma itself the first effect of the loss of heat and volatiles must be the crystallization of the phase in which it is most nearly saturated. There is little doubt that in the Blashke Island complex it was first chromite and then a forsteritic olivine. The initial crystallization of olivine should certainly take place most rapidly around the margins of the complex where cooling is most rapid. However, other factors are working in the opposite direction. Under high vapor pressures, heightened by the crystallization of olivine, there will be an outflux toward cooler regions of fluid from the center of the mass whether it is a supercritical fluid or a liquid with high vapor pressure or two fluid phases, one liquid and rich in silicate components and the other gaseous and aqueous. If there were a silicate-rich liquid phase much of the transport of chemical components can have taken place by a direct increase in liquid concentration in the cooler margins of the mass, the moving fluid carrying with it larger concentrations of more soluble components. There will also be an exchange of components with the enclosing rocks. To explain the Blashke Island complex we must assume that lime and silica, above all, were transported down this temperature and fluid-concentration gradient until a more or less steady state was set up in the magma with the interior very hot, relatively dry, low in lime and silica, and high in magnesia, and the outer margins lower in temperature, richer in fluid, and high in lime and silica.

We may now envisage a condition where in the cooler, more fluid, more siliceous, and calcium enriched margins of the complex augite becomes the stable phase and early-formed forsteritic olivine is actively replaced and resorbed. At the same time in the core of the mass olivine continues to be stable and continues to crystallize. With the cooling of the complex the crystallization of augite proceeds inward or perhaps takes place more or less simultaneously in a broad outer zone, and crystallization of olivine proceeds outward. At any given time the main uncrystallized, or partially uncrystallized, residue of the complex will lie between the core of olivine and the crust of augite and be intermediate in composition between them. Irregularities in the contact between dunite and augitite can be explained by sagging and slumping of the core and the crust into this mushy residue and injection of the residue into both rocks; thus can be explained the intrusive masses of augite dunite and wehrlite with a composition corresponding to the border facies between dunite and olivine augitite.

Several other troublesome features can also be explained. The replacement relations of augite to olivine relatively low in iron are demanded by the hypothesis. The augite stable in the outer part of the complex is relatively lower in iron than the olivine that it replaces. An enrichment of iron in an interstitial residue may thus be built up, eventually crystallizing as the high-iron olivine that shows late relations to augite, or locally as interstitial magnetite forming the sideronitic groundmass of the rock, koswite. Cryptic zoning is demanded by the hypothesis because crystallization is taking place down a temperature and concentration gradient from the core outwards. The equilibrium conditions set up may be different than those that would prevail during fractional crystallisation of a basaltic magma and this may explain the displacement of the augite variation curve from that found in common mafic magmas. It may also explain the absence of orthopyroxene as a primary phase.

The essence of the hypothesis is that a gradient is set up from the core of the system outward both in temperature and in the concentration of a number of components. In a region near the center of this gradient there is a change in equilibrium from olivine to augite as the primary stable phase, once something approaching a steady state has been achieved. The mechanism for achieving the gradients and shifts in equilibrium that have been suggested here may not be entirely valid, but the observed petrologic relations seem to require some method of centrifugal differentiation. Diffusion of non-volatile solutes and movement of fluids along vapor pressure gradients must have played a part because of the strong temperature gradient known to have been present and the chemical contrast between the intrusive and the country rocks.

Explanation of chemical variation

The major chemical change taking place between magma and country rock is the migration outward of calcium and magnesium. There is a reciprocal relationship between magnesium and calcium within the ultrabasic part of the complex because calcium is, so to speak, arrested in its outward flight at the borders of the ultrabasic by its fixation in augite. Beyond the complex both gradually decline. This explains the maximum in CaO in the augitite ring. On the other hand, silica was lost by the gabbroized country rock, probably by transfer into the margins of the ultrabasic mass, thus helping to make augite the major stable phase in the outer zone of the peridotite. Very little interchange of alumina took place. It may be reflected in a little interstitial anorthite here and there in the olivine augitite. Alkalies found no resting place in the ultrabasic. They were virtually absent from the original magma and there was no stable solid phase available to take them up at the high temperature and the composition range in which crystallization took place in the complex. Alkalis no longer present in the granulitized country rocks may have come to rest in notable proportions in rocks beyond the gabbroized zone. The wholesale replacement of quartz, hornblende, and biotite by granulitic orthoclase in a rock several hundred feet beyond the gabbro has been noted (specimen 232, page 100). The data on rocks beyond the gabbroized zone are unfortunately not complete enough to develop this idea in detail. The presence of alkali feldspar and biotite in outer facies of the gabbro has been noted, as well as the appearance of biotite and alkali feldspar in the gabbroic granulite where the grade of metamorphism is lower.

Origin of minor rock types

Augite dunite and wehrlite dikes

An explanation for the origin of these dikes has already been given in the general outline of the hypothesis on page 182.

Augitite dikes in dunite

These dikes can be explained by the re-entry into the dunite part of the complex, at a later stage, of the same fluid components that brought about the crystallization of augite and resorption of olivine in the outer parts of the complex. These fluids enter early fractures in the dunite core after it has cooled into the augite range of stability and they react with the olivine wall rock to produce augite. The process has been described in detail by Bowen (Bowen and Tuttle, 1949, pp. 459-460).

Gabbroic pegmatite

Gabbroic pegmatite represents an association in small, isolated clots, streaks, and dike-like masses of an aluminous phase, anorthite, with late-crystallizing primary phases of the ultrabasic, mainly iron-rich olivine and hornblende, along with augite. It can equally well be regarded as a late differentiate in which a tiny fraction of alumina present in the original magma appears, the alumina may be regarded as having diffused into the complex from the country rocks, or the pegmatites may represent the reaction of the magma with aluminous inclusions. No serious objection can be seen to any of these modes of origin. On the whole, the sporadic distribution of the bodies, almost all near the outer margin of the olivine augitite ring, points toward their origin by reaction with aluminous inclusions, and areas of disseminated interstitial anorthite may indicate limited diffusion of alumina from inclusions.

Dikes of the beerbachite group

The dikes of the beerbachite group, which actually range in composition from olivine microgabbro to hornblendite, commonly have a slight to strongly developed granulitic texture. In mineralogy and texture they closely approach some of the granulites of contact metamorphic origin. However their dike-like relations to the enclosing olivine augitite and gabbro are clear cut. MacGregor (1931) has called attention to the similarity between Scottish granulite produced by reaction between hot basic magma and basalt inclusions and beerbachites from the type locality in Saxony, and has taken issue with a conclusion reached by Klemm (1926), in a paper not accessible to the present author, that the Odenwald beerbachites are hornfelsed inclusions of sedimentary rock. MacGregor's contention is that the chemical composition of beerbachite is so similar to that of igneous rock that it must be derived from the granulitization of igneous rock, as is clearly the case with Scottish granulites. Both investigators regard the rock as derived from granulitization and mobilization of inclusions. In the Blashke Island complex the beerbachite dikes are probably derived from inclusions also. Where they appear in the olivine augitite they have an anomalous composition and where they appear in the gabbro they are strikingly similar in mineralogy and texture to clearly defined inclusions in the same rock. The question is what kind of inclusions are they and what has happened to give them their dike-like relations.

The very interesting and unusual rock listed as specimen 390, item 103, table 1, offers a fruitful point of departure for the discussion of this problem. The rock has been described and discussed on pages 40-41, 81, and 95-96. and a chemical analysis is given under column M of table 2. The rock is a granular aggregate of colorless diopsidic augite and andradite garnet. It has the highest calcium content of any analysed rock in the complex, is low in alumina, and has normal iron content for its position in the complex. It appears quite certain that this rock must represent a product of reaction between limestone and the ultrabasic magma, but the dike-like relations of the rock to the olivine augitite are sharp and clear. This rock is almost proof positive that inclusions in hot magma that contain phases not stable in the magma break up, decompose, and become softened and partially fused to the point where they flow readily and that they can maintain this state under the proper conditions until the enclosing rock has solidified to the point where it can fracture. This particular rock was one of extreme original composition and this is reflected in the unusual composition of the final product.

The augite-andradite rock clearly establishes dike-like relations for a rock obviously derived from an inclusion, and thus is easier to accept the same origin for rocks more nearly like common igneous rocks in mineralogy and composition. However, it is a question if the unusual composition of specimen 390 proves that differences in composition in the original inclusions will always be obvious in the final product. This author thinks not. Specimen 390 was probably derived from a pure marble, of which some beds are present in the surrounding sedimentary rocks. It represents the introduction of a high-calcium, low-alumina body into that part of the complex saturated with a calcium-rich phase. Under these conditions the tendency to lose its excess calcium is not large and all it can do is take up silica and magnesia until a stable phase can form. On the other hand, let any kind of aluminous rock be introduced and it immediately takes up calcium to form the plagioclase feldspar stable under the existing conditions plus a suite of ferromagnesian silicates. Thus all aluminous rocks of whatever origin are likely to approach gabbro in mineralogy and chemical composition when in contact with hot gabbroic and more basic rocks. The gabbroic granulites derived from diverse original rock types around the complex prove the truth of this deduction, and abundant evidence is given by Grout for the conversion of slates into gabbroic granulite near contacts with the Duluth gabbro. Grout cites numerous supporting references in this paper (Grout, 1933). The conclusion is that the beerbachites can have been derived from inclusions of any kind of aluminous rock enclosed in a hot magma that is extremely rich in calcium and magnesium.

The diversity of dikes of the beerbachite group appears to be partly a function of position in the complex, there being some tendency for olivine microgabbros to occur well within the olivine augitite ring and the more hornblendic beerbachites and hornblendites near the outer parts of the olivine augitite ring and in the gabbro. The diversity is also in part a function of the stage in the cooling of the complex at which the dike finally crystallized.

The norm of the hornblendite beerbachite for which a chemical analysis was made (specimen 99, column P, table 2) shows 25 percent olivine indicating that its composition is actually close to that of an olivine microgabbro. The contrasting mineralogy is thus a function of the mode of crystallization. It has been shown that during the later stages of crystallization of the gabbro and olivine augitite, hornblende appears as a primary phase and as a replacement of augite and plagioclase. The mineralogy of the suite of beerbachites parallels this trend with hornblende becoming the major phase at one extreme of the sequence.

Feldspathic vein rock

Balk (1937) has discussed the relationship of late silicic and hydrothermal facies of many intrusive masses to early primary joint systems formed during the late stages of consolidation. Specimen 261, item 117, table 1, for which an analysis is given under column Q of table 2, was collected from a vein or dike, 2 inches wide, occupying a flat-lying joint of a set corresponding in structural relations to the so-called L joints as described by Balk (1937). This rock appears to represent crystallization from the last fluid siliceous fraction capable of forming a rock. Later fluids appear to have mainly reacted with pre-existing minerals to form hydrous alteration products such as serpentine. Little or no reaction between specimen 261 and the enclosing rock (specimen 261, item 80, table 1) can have taken place in view of the altogether leucocratic character of the vein. Presumably this specimen gives an indication of the composition of the last siliceous fraction of magma after prolonged crystallization and reaction with enclosing rock. It is rich in silica, alumina, and soda, but it contains a low percentage of potash. It is another indication that potassium tended to diffuse outward rather than inward toward the cooling mass.

Dikes older than the complex

The analysed hornblende porphyry dike rock (column S, table 2) fits well into a prolongation of the variation trend shown by the major units of the complex, but there is little direct evidence to connect this group of rocks to the complex. If related, they are forerunners of the complex generated at greater depth and emplaced ahead of the ultrabasic mass. Their textures show that the smaller ones were quickly cooled against relatively cold country rocks. If they are not forerunners of the ultrabasic intrusion, they indicate that there was a Silurian or later episode of intrusive igneous activity in southeastern Alaska prior to the Coast Range Jurassic or lower Cretaceous activity. This author is inclined to the opinion that the dikes earlier than the complex are not genetically related to the complex and are connected with some altogether earlier post-Silurian episode of magmatic intrusion.

Origin of petrologic and structural relationships between gabbro, gabbroic granulite, and inclusions

Where wall rocks are in contact directly with peridotite of one kind or another they have been converted into a gabbroic granulite in which the most persistent phases are augite and calcic plagioclase. Hornblende is absent except at a considerable distance from the complex. Where wall rocks are in contact with gabbro or appear as inclusions in gabbro hornblende is an abundant and essential phase. The compositions of composite samples of gabbro and gabbroic granulite are closely comparable as shown by the chemical analyses in columns U and Y, table 2. The highest ranks of gabbroic granulite contain very small amounts of hydrous phases, while hornblende is abundant in the gabbro.

An explanation for these relationships may be found in the mode of origin suggested for the gabbro. The gabbro is supposed to have formed by chemical transformation of aluminous wall rocks along the same lines shown by the gabbroic granulite, but in the case of the gabbro the process was culminated by the partial or complete dissolution into a mobile magma by volatile fluxing and partial melting, of the transformed country rock. The reason why this took place along some parts of the contact and not on others is probably directly due to original composition, to the extent to which the wall rocks were permeable to volatiles, and to the volatile concentrations to which they were exposed. Permeable rocks of suitable composition were dissolved and fused. At other points in the complex, particularly along the western border which appears to dip slightly inward, the concentration of volatiles was less and the rock less open to volatile impregnation, so less gabbroic fluid was formed. Gabbro recrystallizing after partial or complete liquification crystallized at a lower temperature and with higher volatile concentration and so hornblende formed. The lower temperature and higher volatile concentration is reflected in the mineralogy of the inclusions and of the wall rocks of the gabbro that has passed through this magmatic stage.

No chilled borders between gabbro and country rock were seen any place in the complex or in outlying bodies of gabbro related to the complex. This fact is readily explained by the proposed mode of origin. The gabbro formed by heating and chemical transformation of country rock, and the country rock with which it is in contact was only a little less affected by the same agencies, thus there was no abrupt break in the temperature gradient and no chilling effects along contacts.

Origin of certain structural features

Interbanding of wehrlite and augite dunite in olivine augitite

Along the western side of the complex broad, poorly defined bands of wehrlite and olivine augitite are found with gradational relationships. These bands have been considerably modified by late faulting and shearing. Elsewhere in the complex other bands and masses of wehrlite with indistinct boundaries are found. These bodies are usually sub-parallel in orientation to the concentric form of the complex as a whole. They are not sharply intrusive as are the wehrlite and augite dunite dikes that have been described. These bodies are interpreted in one of two ways. They may be residual masses approaching the composition of the original wehrlite magma. Throughout most of the olivine augitite ring original olivine was largely replaced by augite, but locally less permeable texture may have spared some bands of rock from much replacement leaving masses of wehrlite composition with olivine corresponding in composition to that in the margins of the dunite core. On the other hand, the boundary between the region in the complex where olivine remained stable and the outer region where augite supplanted olivine may have shifted inward during the crystallization of the complex. These outer wehrlite bands with olivine corresponding to that in the border facies of the dunite core may represent rocks crystallized at the locus of a former boundary between regions of augite and olivine stability where the rocks of the temporary boundary zone were too well crystallized for more complete replacement by augite when the boundary shifted inward.

Zone of weakness and physical discontinuity between gabbro and olivine augitite

This feature actually represents the major discontinuity in the complex if the gabbro is interpreted as having been derived by transformation of wall rocks. It is the locus of the intrusive contact between country rock and ultrabasic polyphase magma. Later in the history of the complex gabbroic magma may have existed in a mobile state on the side of the contact once occupied by solid country rocks, and solid, nearly completely crystallized olivine augitite may have been present where the magma once lay. Gabbro formed further down along the contacts with the ultrabasic may have moved up along this contact. It thus remained a locus of physical and chemical discontinuity and in later stages may have been open to hydrothermal solutions which caused decomposition of the rocks on both sides.

Intrusion breccias along certain gabbro contacts with country rocks

The generation of a fluid gabbroic magma by ultrametamorphism has been argued at length. It is likely that this kind of magma would form in greater abundance deeper down along the walls of the ultrabasic and rise along the contact with country rock. As it rose it invaded and brecciated ungabbroized country rocks along the walls of the intrusion.

Banding in the gabbro

The banding locally present in the gabbro may be interpreted entirely as a flow structure where the gabbro reached a magmatic stage and flowed, but the intricate swirling, curving, and intersection patterns of this structure are hard to account for under this interpretation because the probable viscosity of the magma makes turbulence during flow unlikely. Nevertheless the structures do have the appearance of a turbulence pattern, at least superficially.

It has been shown that the structure is actually a concentration of late poikilitic hornblende along narrow bands and represents narrow zones along which the late volatile residues were active. Some slight parallelism of plagioclase tablets with the bands has been noted however. It is suggested that this banding may represent strain patterns in a semi-solid mass subject to a combination of shearing stresses relieved by flow. During shear, finely spaced bands of relative compression and tension might form causing late volatile residues to migrate into bands of relative tension. The shearing stress would then be relieved locally by plastic yielding, causing deformation and interruption of strain patterns and the shifting, bending, and reorientation of strain lines.

Origin of polyphase ultrabasic magma

Norman L. Bowen has repeatedly taken up the cudgels against proponents of ultrabasic magma. In his latest publication related to the subject (Bowen and Tuttle, 1949, p. 454), he remarks:

> "Geologists have been, for the most part, reluctant to abandon dunitic or closely related liquid and have sought every avenue of escape from the fenced enclosure to which experimental studies appear to commit them. One by one these avenues have been closed by further experimental studies."

Nevertheless there is a reason why geologists have been reluctant to abandon ultrabasic magmas, and that is because certain field relationships seem to demand them. There may also be a reason why the fenced enclosure built by experimental studies does not encompass an ultrabasic magma, and that may be that ultrabasic magma lies well outside the field delimited by experimentation. The field delimited by experimentation as yet falls far short of the full range of geologic possibilities.

One of the limiting factors has been the obviously low temperatures at which most ultrabasic bodies have been emplaced, and the present author is in complete accord with Bowen's contention that these bodies cannot have consolidated from a magma at the place where they are now seen. However in the Blashke Island complex we have something of a rarity, an ultrabasic with every evidence of having been at a high temperature, perhaps several hundred degrees above the range of experiment. The complex has undergone differentiation. One of the end products has been a body of very pure dunite, but the associated rock shows that the original material contained substantial proportions of other components. Thus a dunitic liquid is not called for.

Furthermore, a fully liquid magma is not called for, only one that is hot, mobile, and reactive. Bowen himself has entertained this possibility in suggesting that an eruptible lherzolitic magma, perhaps half crystalline, might be produced during fractional crystallization of gabbroic magma (Bowen, 1915, p. 31). The interpretation offered here is consistent with the possibility that some fraction of the magma would be solid olivine. It would thus be a magma in the original sense of the word as applied in chemistry, meaning an emulsion or mixture of solid and fluid--hot olivine mud, if you like!

Escape from Bowen's enclosure rests on these considerations. In the shadow of his monumental contributions to petrology it admittedly may seem like no more than a wistful peek through a knothole.

A polyphase peridotite magma may originate in several ways. Hess (1938) has vigorously advocated the development of a hydrous peridotite magma by partial fusion of a peridotite layer during crustal downbuckling at the beginning of a period of deformation. Partial fusion might be brought about both by an elevation of temperature and by local release of pressure attendant upon crustal stresses. Mead (1925) has called attention to the fact that brecciation in solids causes increase of volume and this results in an influx of available fluids into the porous spaces of the expanded masses. Once partial fusion has taken place, a polyphase magma is in being. It may then be capable of intrusion as a plastic mass or by elastic response to the opening of any avenue of weakness in the containing rocks as advocated by the author for the intrusion of certain kinds of clastic dikes (Walton and O'Sullivan, 1950).

Polyphase peridotite magma may also represent the accumulated residues in deep crustal chambers of preceding periods of geosynclinal volcanism. The Jurassic-lower Cretaceous(?) section laid down immediately prior to the beginning of Coast Range deformation and deep-seated intrusive activity contains much volcanic material (Buddington and Chapin, 1929, pp. 158, 165-173, 255-256).

Relationship of the Blashke Island complex to other types of ultrabasic intrusions

The hypothesis that has been offered in this paper applies primarily to the Blashke Island complex and is not offered as a general hypothesis to explain all peridotite intrusions. For example there is no reason to apply the hypothesis to ultrabasic layers in stratiform complexes of the Bushveld type. Nevertheless, if the hypothesis has any validity, it must have some general applications. The hypothesis is directly applicable to only a relatively few ultrabasic complexes that show concentric zoning and evidences of high temperature. More commonly ultrabasic masses have little orderly internal arrangement of component rock types, show strong deformational structures and fabrics, produce little contact effect on enclosing rocks, and many consist simply of an almost monomineral mass of dunite or serpentine derived from dunite.

An explanation for the relative scarcity of concentrically zoned ultrabasic masses with the high degree of regularity and the high temperature effects of the Blashke Island complex as compared with more common peridotite and serpentine intrusions may be found in the tectonic setting of peridotitic rocks. Ultrabasic rocks are generally found among the first rocks to be intruded during a petrogenetic cycle (Benson, 1926 , pp. 75-76) and according to Hess (1938) their intrusion takes place during the earliest period of strong deformation in an orogenic belt. An ultrabasic intrusion therefore commonly undergoes a prolonged period of regional deformation after its emplacement during which its primary structures and relationships to surrounding rocks may be completely or partially obliterated. If the mass becomes wholly or partially serpentinized it becomes peculiarly susceptible to tectonic displacement and during regional folding may undergo further movement by plastic flow for considerable distances in a condition in which it will have no contact effects on enclosing rock. Bowen (Bowen and Tuttle, 1949, p. 455) has pointed out that olivine itself lends readily to solid flow under stress because of its atomic structure. An aggregate of olivine in the core of a complex such as that described in this paper might contain a large amount of interstitial supercritical water vapor for a considerable period after the formation of the complex, and this would lend the dunite part of the complex especially to injection and displacement by the method of elastic response advocated by this author to explain certain intrusions of clastic material. All of these factors conspire to cause the destruction of the primary structures of peridotite intrusions and present them to view in a variety of forms produced by varying degrees of deformation. Only a relatively few complexes like the Blashke Island complex may ever have escaped the later deformation which follows in the normal course of events, but differentiated complexes like the Blashke Island complex may have been the proximate source of many ultrabasic bodies, particularly the nearly monomineral ones that must have undergone a high degree of differentiation at some other place. Few ultrabasic masses may have had the opportunity to carry the process of differentiation to completion before undergoing deformation. The Blashke Island complex may afford a rare insight into a process seldom carried to completion and even more rarely preserved and brought to view in accessible parts of the earth's crust.

Regional relationships of ultrabasic intrusions in Alaska and western Canada

Alaska and contiguous areas of British Columbia and the Yukon Territory are far from adequately known geologically. A large percentage of these areas has never been mapped. Much of what has been mapped has been done on such a small scale and by such hasty reconnaissance methods that many bodies of the magnitude of typical ultrabasic complexes can have easily escaped attention or been lumped with other rock units. Nevertheless a survey of Alaskan and Canadian literature has revealed more than forty localities containing intrusive bodies of peridotite, serpentine derived from peridotite, or closely related rocks. Many of these localities contain a number of bodies, so that the total number of individual ultrabasic masses known is a good deal more than a hundred. While there are doubtless many more yet to be reported, the distribution of the known peridotite and related rock masses in place and time is probably adequate to give a true picture of the regional relationships.

The regional and chronologic distribution of ultrabasic rocks in Alaska and geologically related areas of Canada are summarized in figure 2, and table 8. The locations of all ultrabasic rock bodies known to the author have been plotted on figure 2. The areas, references, rock types, and geologic ages of the bodies plotted in figure 2 are listed in table 8. In order to bring out the geologic relations of the ultrabasic rocks, figure 2 also shows the areas underlain by other plutonic rocks. These rocks consist largely of batholiths, stocks and bosses of diorite, granodiorite, granite, and syenite. The data on plutonic rocks other than ultrabasic have been taken from the Geologic Map of North America (Stose, 1946), supplemented in British Columbia by a recent compilation by Armstrong (1946, fig. 2, p. 5). Hess (1938) has shown some of the ultrabasic localities in a compilation of peridotite intrusions throughout the world. The geologic ages given for the ultrabasic rocks listed in table 8 are those assigned by the original author unless enclosed in parentheses. Geologic ages enclosed in parentheses have been assigned by the present author on the basis of the positive evidence for age cited by the original author plus the later correlations made by other workers in adjacent areas or by the present author in the light of the present compilation. In compiling figure 2 and table 8, attention has been focused only on truly ultrabasic rocks believed to be of intrusive origin. Many geologic compilations are vitiated by including too many items of diverse origin and genetic significance. This must be avoided if true genetic relationships are to be illuminated, as Hess (1938, p.272) has pointed out in connection with the problems of peridotite intrusions. Therefore many bodies of basic rock variously described as hornblendite, gabbro, intrusive greenstone, peridotitic differentiates of gabbroic or basaltic masses, or inadequately described have been excluded from the present compilation. Doubtless some of these rocks are genetically connected with the intrusive peridotites, but others are clearly marginal facies and differentiates of more silicic rocks, or greenstones of metamorphic origin, so most of them have been eliminated. However, a few of possible significance have been shown on the map by a separate symbol.

Table 8. Ultrabasic and basic intrusions mapped in figure 2.

Area and reference	Rock type	Age
Alaska, West of long. 141°W.		
1. Kobuk R. valley, northern Alaska; Smith, P.S., Bull. 815	Serpentine	Devonian(?)
2. Yukon-Tanana region; Mertie, Bull. 872	Serpentine in part derived from peridotite	Late Devonian
3. Nelchine-Susitna region; Chapin, Bull. 668	Serpentine, intrusive	Intrusive into Carboniferous or older. (Late Triassic-Early Jurassic)
4. Copper River region; Moffit, Bull. 894	Peridotite	Post-Permian(Late Triassic-Early Jurassic)
5. Copper River region; Kingston & Miller, Bull. 943-C	Peridotite	Later than post-Permian deformation. (Late Triassic Early Jurassic)
6. Kenai Peninsula; Guild, Bull. 931-G	Dunite complex	Late Jurassic-Early Cretaceous
7. Iliamna Bay; Martin & Katz, Bull. 485	Peridotite dike	Cuts Middle Jurassic granite
8. Goodnews Bay; Mertie, Bull. 918	Dunite complex	Late Cretaceous
9. Mt. McKinley region; Brooks & Prindle, p. 70 Reed, Bull. 849-D	Serpentinized peridotite not found in place, and peridotite not mapped.	(Mesozoic)
10. Matanuska area; Paige & Knopf, Bull. 327	Peridotite	Unknown

Southeastern Alaska

11. Baranof Island; Guild & Balsley, Bull. 936-G; Kennedy & Walton, Bull. 947-D; Reed & Coats, Bull. 929	Dunite complex and serpentine sills	Late Jurassic
12. Fords Terror, Juneau Dist.; Buddington, Bull. 800	Dunite, cut by granite dikes	Early in Late Jurassic-Early Cretaceous orogeny
13. Tracy Arm, Juneau Dist.; Buddington, Bull. 800	Saxonite	Early in Late Jurassic-Early Cretaceous orogeny
14. Kane Peak, Kupreanof Id.; Buddington, Bull. 800; Author	Peridotite complex	Late Jurassic-Early Cret ceous, Early Cretaceous preferred
15. Blashke Islands; Author	Dunite-pyroxenite complex	Late Jurassic-Early Cretaceous
16. Mount Burnett; Kennedy & Walton, Bull. 947-D; Author	Dunite-pyroxenite complex	Late Jurassic-Early Cretaceous
17. Duke and Annette Ids.; Koschmann, Trans. Am. Geophys. Union, 1935	Saxonite-hornblendite complex	Not given (Late Jurassi Early Cretaceous)
18. Kasaan Peninsula, Salt Chuck; Wright, p. 87	Pyroxenite-gabbro complex	Devonian(?) (Late Juras Early Cretaceous)

Yukon Territory, Canada

19. Whitehorse Sheet; Cockfield & Bell, Mem. 150	Peridotite and pyroxenite	Pre-Devonian (Jurassic)
20. Little Salmon Area; Cockfield, Summ. Rept. '28	Serpentine	Carboniferous or older(?) (Jurassic)
21. Pelly River; Johnston, Mem. 200, map 394-A	Serpentine	Pre-late Cretaceous (Jurassic-Early Cretace
22. Laberge Sheet; Cockfield, map 372-A	Peridotite, serpentine hornblendite	Jurassic--cut by Jurassi or later granite.
23. Teslin-Quiet Lake Area; Lees, map 350-A	Serpentine	Jurassic--cut by Jurassi or later granite.
24. Conrad and Whitehorse Dists.; Cairnes, D.D., Summ. Rept. '06	Serpentine	Unknown (Jurassic to Early Cretaceous)

British Columbia, north of lat. 54°

25. Atlin mining district; Gwillim, An. Rept., v. 12, '99, map 742	Serpentine, "Gold Series", includes much intrusive serpentine, derived from dunite and peridotite.	Mesozoic, earlier than acid intrusions. (Jurass Early Cretaceous)

26. Atlin-Telegraph Creek traverse; Cockfield, Summ. Rept. '25	Serpentine, derived from intrusive peridotite. Contiguous to and includes part of "Gold Series" (above)	Late Paleozoic-early Mesozoic. (Jurassic-Early Cretaceous)
27. Eagle-McDame Area; Hanson & McNaughton, Mem. 194	Peridotite and serpentine	Jurassic-earlier than Cassiar Batholith
28. Aiken Lake map area; Armstrong & Roots, paper 48-	Peridotite, serpentine pyroxenite, hornblendite	Jurassic-earlier than Omineca acid intrusions
29. Takla Dist.; Armstrong, map 844-A	Peridotite and serpentine	Jurassic-earlier than acid intrusions
30. Fort Fraser map area, W. half; Armstrong, Trans. Roy. Soc. Can. v. 34 & map 631-A	Peridotite and serpentine	Jurassic-earlier than acid intrusion
31. Fort Fraser map area, E. half; Gray & Armstrong, map 630-A	Peridotite and serpentine	Jurassic-earlier than acid intrusion

British Columbia, South of Lat. 54°, excepting 49th Parallel Survey

32. Sandon, Slocan & Ainsworth Dists.; Cairnes, map 273-A	Serpentine	Triassic--cut by post Triassic granite dikes.
33. Tulameen Dist.; Camsell, Mem. 26	Dunite-pyroxenite complex	Early Jurassic--cut by Eagle granodiorite
34. Cadwallader Creek Area and Gun Lake Area; Cairnes, Mem. 213 & maps 431-A, 430-A.	Dunite, pyroxenite & serpentinized peridotites	Late Jurassic--cut by Bandor intrusives
35. Bridge River Map Area; McCann, Mem. 130	Serpentine, mapped as extrusive, but shown by Cairnes, Mem. 213, to be intrusive in adjacent area.	Triassic (Late Jurassic)
36. Yale Dist.; Cairnes, Summ. Rept., 1929	Serpentine derived from peridotite	Late Jurassic-Early Cretaceous. Cut by Coast Range diorite.
37. Wolfe Creek Area; Bostock & McNaughton, map 596-A	Peridotite	
38. Olalla; Bostock, map 628-A	Pyroxenite-gabbro complex, doubtfully related to peridotite	Lowest post-Triassic. Cut by syenite and granite

British Columbia, 49th Parallel, Reference; Daly, Mem. 38

39. Map 84A	Cross-cutting dunite dikes	Late Paleozoic(?)
40. Map 85A	Dunite	Late Paleozoic-Triassic
41. Map 86A	Basic complex cut by orbicular peridotite with olivine nodules	Late Paleozoic-Triassic
42. Maps 81A, 82A, 83A	Dunite, Harzburgite and serpentine intrusions	Mesozoic, earlier than Trial Batholith (Jurassic-Early Cretaceous)
43. Map 88A	Harzburgite and dunite	Post-Jurassic to Oligocene
44. Page 543	Dunite dike	Not given

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Figure 2 and table 8 show that there are at least six and possibly more episodes of ultrabasic intrusion in Alaska separated in time and place, as follows:

a. A northern belt in the Brooks Range of lower Devonian age, barely suggested by the serpentines reported in the Kobuk River area. A dearth of information rather than a paucity of intrusions probably explains the lack of other ultrabasic bodies shown in northern Alaska.

b. Two parallel upper Devonian belts in the Yukon-Tanana region that do not invade Mississippian rocks and are cut by Mesozoic intrusions.

c. A lower middle-Mesozoic belt in the Copper River region said to be later than a post-Permian period of deformation and older than silicic intrusions that do not invade middle Jurassic and younger rocks.

d. Upper Jurassic to lower Cretaceous bodies in the Cook Inlet area(nos.6, 7 & 10).

e. Upper Jurassic to lower Cretaceous complexes in southeastern Alaska, earlier than the Coast Range batholith and related silicic rocks.

f. A post-middle-Cretaceous and pre-early-Tertiary complex (no. 8) at Goodnews Bay, not deformed by a mid-Cretaceous orogeny in the Kuskokwim region and cut by early Tertiary granites.

g. A suggestion based on very inadequate information of a peridotite belt in the Alaska Range.

Each of these groups of intrusions is located in a belt that was tectonically active prior to or during intrusion, and in each belt the peridotite intrusions were followed by the emplacement of batholithic masses of silicic rock. The older belts are in central and northern Alaska, and the younger intrusions are along the Pacific coast (excepting the Goodnews Bay complex, no. 8) and belong to the early part of the period of intrusion and orogeny that began in the Jurassic and extended into the Cretaceous, culminating in the Coast Range batholith. Large parts of the mountain ranges along the coast from southeastern Alaska to Prince William sound are virtually unmapped and unexplored so that the upper-Jurassic-lower-Cretaceous belts of intrusion in the Cook Inlet area and in southeastern Alaska may well be connected by as yet unreported peridotite intrusions. The author has collected serpentine pebbles from Oligocene tillites in the Robinson Mountains a few miles northwest of Mount Saint Elias.

The ultrabasic intrusions of southeastern Alaska are closely related in time, place, and geologic relationships to the peridotite intrusions of the Canadian areas. The Canadian ultrabasic masses are apparently largely confined to a single, though perhaps interrupted and relatively prolonged, episode of intrusion, except for several areas along the International boundary at the 49th parallel. Some of the earlier workers in the Yukon Territory and northern British Columbia were inclined to place some of the serpentines and peridotites of these areas in the late Paleozoic or early Mesozoic because they are enclosed in Paleozoic rocks. The only upper limit of age is that these rocks are earlier than upper Mesozoic silicic intrusions. Later workers have placed similar rocks in adjacent areas at the beginning of the late Mesozoic cycle of intrusive activity, so that these rocks are here regarded as Jurassic or lower Cretaceous.

In southern British Columbia, Daly has classified several ultrabasic bodies along the international boundary as late Paleozoic. Cairnes classifies the easternmost peridotite area shown in figure 2 as Triassic, but the only upper limit of age is that these bodies are cut by post-Triassic granite dikes that may be late

Mesozoic in age. Camsell states that the ultrabasic rocks in the Tulameen District are early Jurassic because they are cut by the Eagle granodiorite which is overlain unconformably by Cretaceous. The other ultrabasic bodies in southern British Columbia are generally regarded as belonging to the earliest phase of the Coast Range batholithic intrusions and all are said to be older than the acid rocks. However Daly regards one body (no. 43) as probably early Tertiary. Thus there is possibly a considerable range in age in southern British Columbia, but this seeming range may, in large part, be due to conflicting interpretations and difficulties in exact correlation.

Hess (1938, p. 278) has indicated that some of the easternmost ultrabasic intrusions lying along the 49th parallel may belong to a Paleozoic period of intrusion, but the present study does not give much support to this view.

The areal distribution of ultrabasic intrusions in southeastern Alaska and Canada shows a distinct pattern in relation to the batholithic masses. One large area containing numerous ultrabasic masses is located along the 49th parallel at the southern end of the Coast Range batholith. A second is located at the southern end of the Omineca-Cassiar batholithic constellation, and a third is at the northern end of this broad arc of plutonic masses. This third cluster of ultrabasic intrusions is practically contiguous with a fourth group extending up into the Yukon Territory at the northern end of the Coast Range batholith. The fifth group is in southeastern Alaska where there are numerous satellitic stocks and bosses passing northward into a zone of dioritic to granitic masses of batholithic proportions extending from Baranof Island northward into the Yukons.

Each of these areas where ultrabasic intrusions are concentrated appears to be an area where zones of major batholithic masses pass beneath the present area of exposure and where many minor batholiths, stocks, and bosses suggest that further unroofing would reveal an almost continuous batholithic mass not far beneath. In other words, the ultrabasic intrusions appear to be related in space to batholithic roof zones and to precede the emplacement of the batholith in time.

Hess (1938, p. 269) has concluded that ultrabasic intrusion accompanies the first great deformation of an orogenic belt and are absent in later deformations.

This close correlation in space and time is certainly not adventitious. It strongly suggests a genetic connection, but it is not necessary to conclude that the ultrabasic rocks and the silicic batholithic rocks are differentiates of a common magma. On the contrary, the rocks of most extreme composition and highest density are found emplaced above and in advance of the batholitic rocks. They are not marginal and gradational with the major granodiorite masses, but are invaded by the acid rocks at a distinctly later period. It is true that the batholithic masses commonly display basic marginal facies of hornblendite and gabbro (Buddington and Chapin, 1929, pp. 236-239), and that some of the ultrabasic bodies are also bordered by gabbroic differentiates, but these are mere gestures in the right direction across a broad gulf that is nowhere found bridged by a continuous sequence of rocks that can be clearly shown to have been derived from a common parental magma. Hess (1938, p. 263) has shown that a genetic distinction is to be made between peridotite intrusions of the type discussed here and the peridotite differentiates of basaltic magmas that are formed in a different crustal environment.

Differentiation from a common magma seems to hold the greatest appeal for geologists, but there are other kinds of genetic relationship. The valid relationship between ultrabasic intrusions and batholithic emplacement that can be observed is that they are both products of a common sequence of crustal processes. Major orogenic disturbances initiate a cycle of petrogenesis beginning with the intrusion of ultrabasic rocks and culminating in the formation of batholiths. The ultrabasic rocks and the granitic rocks are products of a common process rather than a common magma. By analogy one might point out that the labors of a geologist may produce both perspiration and hypotheses, but few would suggest that they spring from a common sub-cutaneous reservoir.

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Notes on the Kane Peak complex

Introduction

The rocks of the Kane Peak complex crop out along the shore of Kupreanof Island from Cape Strait southeastward for a little more than a mile. The complex extends inland southwestward for almost two miles to a small lake or tarn occupying a cirque south of the summit of Kane Peak. Rocks of the complex extend to within a few hundred feet of the summit of Kane Peak and form a prominent shoulder with a small subsidiary summit. The extreme ferromagnesian composition of the rocks on this shoulder causes them to be hostile to vegetation and it appears, when seen from boats passing along Frederick Sound, as a large, bare, red-brown rock outcrop of uncommon aspect. The complex has thus excited the passing interest of many Alaskans, who are always alert for signs of possible mineralization. Many prospectors have visited the area in the hope that it represents the gossan of a mineral deposit, and the feeling that "there is something there" remains in the minds of many, despite disappointing assays and investigations.

The location of the Kane Peak complex is shown on figure 1, page 8, and as locality number 14 on figure 2, page 12. A general view northeastward across the cirque and tarn toward the bare shoulder of Kane Peak with Frederick Sound and the mountains of the mainland in the background may be seen in plate 3. Relief in the area is sharp, rising from sea-level to summits with elevations of more than 3,000 feet in less than two miles. However the northeastern half of the area underlain by the complex consists of gentle slopes and terraces, for the most part, with an almost unbroken cover of muskeg and somewhat stunted forest growth. In this part of the area outcrops are almost confined to the wave-washed shore and the bed of a small stream crossing the complex. The precipitous southwestern half of the area contains many bold outcrops, where underlain by peridotite and pyroxenite, but outcrops on many steep slopes underlain by rocks less hostile to plant growth are disappointingly scarce.

The Kane Peak complex was briefly commented upon by Buddington (Buddington and Chapin, 1929, p. 192) who gave short petrographic descriptions of some of the rocks associated with the complex. He describes the part of the complex forming the prominent outcrops on the flank of Kane Peak as a core of pyroxenite encircled along the south and east sides by a border of dunite and wehrlite. These rocks are distributed in the way Buddington has indicated, but subsequent investigation has proved that it is the pyroxenite that is marginal to a core of dunite and wehrlite, rather than the reverse.

The area was again visited for a few days by George C. Kennedy and the present author in 1943, and a short account of the salient geologic features of the complex was published (Kennedy and Walton, 1946, pp. 78-80). At that time the essential marginal relationship to dunite of pyroxenite and other more silicic and calcic rocks was recognized. The present account adds new data and details and gives additional insight into the petrology and structure of the complex.

The author and his assistant, Ivan Tolstoy, camped for 10 days in the area in August, 1946, and prepared a topographic base map by chaining, pace-compass, and aneroid barometer. Detailed geologic mapping and study of the area was mainly confined to the southwestern part of the complex and its enclosing rocks. A topographic and geologic sketch map is given here as figure 18, page 210.

The ultrabasic rocks

The major rock units of the Kane Peak complex are, for the most part, strikingly similar to the rocks of the Blashke Island complex. The complex consists of a central area underlain by dunitic rocks. Marginal to these rocks, particularly at the southwestern end of the complex, is a border zone of olivine augitite. However, unlike the Blashke Island complex, the olivine augitite mass does not form a complete ring around the more olivine-rich rocks, but is locally absent and is represented by a narrow border zone of biotite lehrzolite or biotite wehrlite. The Kane Peak complex has not been sufficiently well mapped to delineate a core of dunite free of augite, as there is in the Blashke Island complex, but reconnaissance indicates that wehrlite, commonly passing into olivine augitite, is typical of the borders of the mass and that augite tends to be less abundant, or even absent, toward the center of the mass. The existence of a dunite core substantially free of augite forming a considerable fraction of the complex has not been fully demonstrated, and it is doubtful that one exists that is as well-defined as the dunite core of the Blashke Island complex. Most of the olivine-rich rocks are partly serpentinized, but locally they are unusually fresh.

The Kane Peak complex is different than the Blashke Island complex in several petrologic aspects. There is no extensive development of gabbroic rock surrounding the peridotite mass. Locally, and particularly along the northwestern border of the complex the marginal facies is a hornblendite with abundant remnants of augite largely replaced by hornblende and streaks containing coarse calcic plagioclase. Only patches of this rock a few feet across locally approach a gabbro in mineral composition. Elsewhere various rather distinctive facies of the peridotite are in direct and sharp contact with country rocks, but the country rocks are granulitized and changed in composition for distances of only a few tens of feet to perhaps 200 feet from the contact, and the change in composition is by no means as extreme as that observed around the Blashke Island complex.

Several facies or variants of the peridotite in the Kane Peak complex have no counterpart in the Blashke Island complex. At one place the southern contact of the complex with the country rocks may be seen to dip inward toward the center of the complex about 40°. This place is shown on the geologic map as the most southerly outcrop of peridotitic rocks. A narrow erosional remnant of the peridotite mass appears in the form of a ledge running eastward along a northward-sloping hillside. Somewhat granulitized hornblende schist underlying the peridotite is exposed up-slope from this ledge, and reappears again down-slope from the ledge. The slope of the hillside is thus approximately the same as the dip of the contact, and where the peridotite has been eroded away along the stream valley below the ledge, the floor of the complex is again exposed. This exposure affords a unique opportunity to see the peridotite mass in contact with enclosing rocks over several hundred feet of relief, and clearly demonstrates the inward-dipping, basin-like structure of the contact at this particular place. The rock in this ledge is mostly a biotite wehrlite, but within ten to twenty feet of the contact with hornblende schist hypersthene appears in quantities up to 10 or 20 percent of the rock. Appreciable amounts up to several percent of the sulfide minerals pyrrhotite, pentlandite, and chalcopyrite are also sporadically distributed through the rock, but no masses of sulfide-bearing rock of economically exploitable dimensions were seen. However such masses may exist. The rock is porphyritic in texture. Olivine and augite crystals 2 to 5 mm. in cross-section are distributed through a granular groundmass of grains less than a millimeter in cross-section consisting mainly of augite and hypersthene with a little very calcic plagioclase. Some large, poikilitic crystals of greenish-brown hornblende and a little pale, reddish-brown biotite is also present. The rock may be called a biotite lehrzolite.

At one locality within the olivine augitite mass at the southwestern end of the complex an outcrop of rock consisting of coarse biotite and augite was noted. The biotite encrusts and partly replaces well-formed augite crystals. The rock may be a product of hydrothermal attack on olivine augitite. Its field relations to other rocks of the complex were not exposed.

At the south end of the exposures along Frederick Sound the peridotite of the complex appears to pass gradationally over a distance of about 1,700 feet from an almost completely unserpentinized enstatite-biotite dunite consisting largely of olivine with unusually well-developed 100 and 010 cleavages and containing accessory biotite, hornblende, and enstatite, through a tough, fine-grained, little-serpentinized wehrlite, to an equally fresh, fine-grained olivine augitite. Most of the olivine augitite of the Blashke Island complex is notably coarse grained, and the texture of these rocks as well as the accessory biotite, hornblende, and enstatite in the dunite, and the cleavage in the olivine is distinctive by comparison.

Another distinctive rock is present, apparently as a metamorphosed inclusion within wehrlite, about 350 feet from the southern border of the complex on the shore of Frederick Sound. The rock is a hypersthene amphibolite consisting principally of a gray-green, monoclinic amphibole that is almost colorless in thin section, Ny = 1.633 ± 0.002, moderately large, negative optic angle, Z angle β = 16° ± 1°. The rock contains 10 or 15 percent of hypersthene partially replaced by the amphibole and is liberally spotted with large, poikilitic, deep greenish-brown hornblende crystals up to a centimeter in cross section that enclose and partially replace numerous crystals of hypersthene and the colorless amphibole. The colorless amphibole is commonly rimmed by magnetite and contains abundant inclusions of magnetite. A carbonate replaces the colorless amphibole in sporadic patches.

Within the prominent mass of olivine augitite at the western end of the complex are numerous narrow layers and dikes of augite dunite and wehrlite similar petrologically to the augite dunite and wehrlite bodies found in the olivine augitite ring of the Blashke Island complex. Parts of this mass of olivine augitite are also penetrated by an indistinct box-work of veins of coarser textured rock a few inches wide containing much very coarse olivine in association with very coarse augite and anorthite. Veins of this type are pictured in plate 9. A specimen collected from one of these coarse, irregular bands revealed an unusual feature. The specimen consists largely of coarse olivine and contains a small cavity similar to the miarolitic cavities seen in granite. Coarse, terminated crystals of augite project into this cavity and perched on the augite crystals are some coarse crystals of penninite up to several millimeters across with the following properties: Ny or No = 1.59, 2V variable in a single crystal from 0° to 20°, optic sign positive, birefringence low, color pale bluish green. The olivine is relatively iron-rich ($Fo_{81.5}Fa_{18.5}$) and the augite is similar in composition to the augite in the surrounding rock. The presence of a cavity of this kind suggests that the box work of coarse olivine-rich veins has been produced by reactions along early-formed intersecting joint systems in the rock brought about by fluids, possibly gaseous, emanating from further within the complex.

The olivine augitite at the southwestern end of the complex also contains nodular masses up to a foot or two in cross section of coarse pegmatoid rock consisting of coarse anorthite, olivine, and augite. Some of these bodies have a concentric structure in the core of which is a cluster of coarse anorthite crystals.

Cryptic zoning

The Kane Peak complex exhibits the same strong tendency toward cryptic zoning in the composition of its principal phases that the Blashke Island complex shows. The following table gives the intermediate refractive index and the probable chemical composition of the principal minerals in several sequences of specimens taken along traverses from within the complex outward to the margins. The composition of augite is estimated from the intersection of the refractive index curves given by Hess (1949, plate I, p. 634) with the trend of variation found in Blashke Island augite as shown by curve A, figure 9, page 65 of this paper.

Table 9

Intermediate refractive index and inferred chemical composition of minerals in Kane Peak peridotites and related rocks. Composition given in atomic or molecular percent.

Rock type and location of specimen	Olivine			Augite				Other	
	Ny	Fo	Fa	Ny	Ca	Mg	Fe	Ny	Composition
A. Traverse from center of complex southwestward to contact with monzodiorite mass south of Kane Peak.									
Dunite, center of complex.	1.676	88	12						
Dunite, near gradational contact with augite dunite	1.682	85	15						
Augite dunite, at contact with olivine augitite	1.684	84	16	1.689	45	41	14		
Augite dunite, tabular mass enclosed in olivine augitite	1.689	82	18						
Wehrlite from an olivine-rich band within olivine augitite	1.690	81.5	18.5						
Olivine augitite, a few feet from border of complex	1.694	79.5	20.5	1.692	44	40	16		

B. Traverse southeastward along shore of Frederick Sound from within complex to contact with granulitized phyllite.

Dunite, 1700 feet from border of complex	1.675	88.5	11.5							
Dunite, 900 feet from border of complex	1.675	88.5	11.5							
Wehrlite, 300 feet from border of complex and in contact with amphibolitized inclusion	1.694	79.5	20.5	1.692	44	40	16			
Olivine augitite, in contact with granulitized phyllite	1.692	80.5	19.5	1.690	44.5	40.5	15			
Granulitized phyllite, in contact with olivine augitite				1.696	42.5	37.5	20	Plagioclase 1.557	Ab50	An50

C. Traverse across transitional contact between augite dunite, wehrlite, and olivine augitite near southernmost outcrop of complex.

Augite dunite, 30 feet from olivine augitite	1.684	84	16				
Wehrlite, 3 feet from relatively abrupt transition into olivine augitite	1.686	83	17	1.688	45	42	13
Olivine augitite, 3 feet from abrupt transition into wehrlite	1.687	82.5	17.5	1.689	45	41	14

D. Specimens near inward-dipping contact between complex and hornblendite gneiss floor.

Biotite augitite, within 20 feet of base of complex				1.694	43.5	38.5	18			
Biotite lehrzolite, 10 feet above base of complex	1.698	77.5	22.5	1.690	44.5	40.5	15	Hypersthene 1.690	En78	Fs22
Augite-hornblende gneiss, estimated to be a few tens of feet below contact with complex				1.696	42.5	37.5	20	Plagioclase 1.557	Ab50	An50
Biotite-hornblende schist, 1,300 feet from contact with complex								Plagioclase 1.549	Ab65	An35

To summarize the relationships shown by the data in table 9, olivine ranges from $Fo_{88.5}Fa_{11.5}$ in the center of the complex to a maximum iron content of $Fo_{77.5}Fa_{22.5}$ in the remarkable biotite lehrzolite porphyry found locally at the contact with granulitized schist. Augite ranges from a minimum iron content of 13 percent in wehrlite within the complex to a maximum iron content of 20 percent in granulitized schist and phyllite. Plagioclase from pegmatoid bodies in the augite dunite part of the complex is anorthite and plagioclase in granulitized rocks near contacts with the complex is of the composition $Ab50\ An50$. Outside the contact-metamorphic influence of the complex the composition of plagioclase is $Ab65\ An35$ or even more sodic. Traces of enstatite have been noted in several thin sections of dunite and augite dunite from within the complex, but at the outer margin of the complex the orthopyroxene is hypersthene of the composition $En78\ Fs22$. A distinct cryptic zoning in composition of all of these phases is clearly indicated, and each of these phases grows progressively richer in its less refractory component from the center of the complex outward. Thus the pattern of variation in mineral composition is comparable to that found in the Blashke Island complex.

Metasedimentary rocks in contact with the complex

The Kane Peak complex is enclosed in part by metasediments that Buddington (Buddington and Chapin, 1929, pp. 163-4) has called Jurassic (?). No fossils have been identified in this group of rocks on Kupreanof Island, and the correlation rests on lithologic similarity and structural relations with rocks from localities many miles distant whose age is better established. According to Buddington it is possible that some of the Jurassic (?) rocks should be correlated with rocks classified as Lower Cretaceous (?), and other rocks placed in this category may belong to much older groups of rocks. Thus the age of the enclosing rocks is doubtfully given as Jurassic-Cretaceous. The present report can contribute nothing to the problem of correlating these rocks, but it was noticed that the metasediments at the northern tip of the complex from Cape Strait westward fo perhaps half a mile consist mainly of dark to medium greenish-gray meta-graywacke in thin but persistant beds up to a few feet thick in which foliation is weak or absent. South of the complex the rock ranges from a light gray, distinctly foliated quartz-rich phyllite to a dark to medium gray quartz-biotite schist with nodular porphyroblasts of muscovite. The complex may therefore be in contact with two rock units of much different age, but since both lithologic types fall within the range of lithologies that Buddington has described as present in the Jurassic (?) sequence, the question cannot be settled on the basis of present knowledge.

Within 20 to about 200 feet of the contact with the ultrabasic complex a decided change can be noticed in the texture and composition of the metasediments. The texture becomes somewhat granulitic, quartz, muscovite, and much of the biotite disappear. The plagioclase increases in anorthite content from oligoclase up into the labradorite range. Garnet and augite appear as new phases, and hornblende becomes very abundant in some of the rocks. Locally the rock is shot through with irregular streaks and zones that approach a gabbroic texture and appearance. The extent and intensity of contact metamorphism is not as great as around the Blashke Island complex, but it is very appreciable.

Intrusive rocks in contact with the complex

In the vicinity of Kane Peak the complex is in contact with an intrusive mass that extends several miles to the west. According to Buddington (Buddington and Chapin, 1929, pp. 192 and 204-5) this mass is dominantly of monzodioritic character, but Buddington noted a facies of this mass near its contact with the ultrabasic complex that he described as a peculiar variant of the normal monzodiorite encountered in southeastern Alaska. This facies he called a hornblende-pyroxene monzodiorite, and ascribed its variation from the normal biotite-hornblende monzodiorite to reaction with the ultrabasic mass.

A specimen selected as representative of the monzodiorite body unaffected by proximity to contacts with other rocks was collected at the edge of the mapped area shown in figure 18, page 210, near the summit of Hunt Peak. This rock is a medium-grained phanerite with an equigranular, allotriomorphic, granitoid texture.

Plagioclase of the approximate composition Ab70 An30 comprises about 40 percent of the rock. Microcline makes up perhaps 20 percent of the rock. Five to 10 percent quartz is present. The principal dark mineral is a dark green hornblende that makes up about 20 percent of the rock. A pale greenish-brown biotite comprises about 10 percent of the rock. Apatite is the only important accessory and a minor amount of secondary epidote is present.

Within 50 yards of the contact of this mass with quartz-biotite schist south of Hunt Peak, the rock takes on a strong gneissic structure owing mostly to a preferred orientation of hornblende, mica, and feldspar grains, but partly to a slight but distinct cataclastic texture. In this rock microcline is absent and the plagioclase is a sodic oligoclase. Epidote is abundant, both secondary after plagioclase and in coarse primary grains. Titanite is an abundant accessory and both biotite and hornblende are more abundant than in the rock characteristic of the mass, represented by the specimen from Hunt Peak. Only a minor percentage of quartz is present.

An entirely different facies of the monzodiorite appears near its contact with the olivine augitite border zone of the ultrabasic complex. A specimen collected 3 feet from a sharp, planar contact with biotite-olivine augitite consists of about 60 percent plagioclase feldspar, Ab60 An40, 30 percent augite, and 5 percent each of hypersthene and biotite. The minerals of the rock are notably fresh. The texture is medium fine, hypidomorphic-granular, and somewhat diabasic. The total absence of hornblende is conspicuous. The specimen described by Buddington as hornblende-pyroxene monzodiorite may have been taken farther from the contact with the ultrabasic rocks and represent a transitional facies between the rock in contact with the ultrabasic rocks and the typical monzodiorite.

A dike about 2 feet wide is exposed for some yards in the bed of the stream draining the tarn south of Kane Peak. The stream follows a fault zone that cuts the complex. Within this fault zone the rocks of the complex and also the metasedimentary rocks in contact with the complex show considerable shearing and shattering. Closely spaced sheeted joints are conspicuous. However the dike appears to be unaffected by this disturbance and is thus later than the fault that cuts the complex. The dike rock is a medium-grained, equigranular, hypidiomorphic quartz diorite consisting of plagioclase, about Ab70 An30, abundant quartz, hornblende, biotite, and titanite. The rock is nearly half hornblende, and the hornblende displays a strong tendency toward idiomorphism. The titanite is unusually coarse and abundant. Muscovite and zoisite are common alteration products. A very small amount of microcline is present. Some thin lamprophyre dikes are also present in the fault zone. If the quartz diorite dike is related to the monzodiorite mass, as it well may be, it establishes the complex as older than the monzodiorite and invaded by the monzodiorite.

The actual contact between the main monzodiorite mass and the rocks of the complex can easily be located within a few feet where it cuts across the shoulder of Kane Peak, but it is apparently a zone of weak rock for its exact nature is concealed by much crumbling and deep weathering. However the map relations indicate that it is probably a relatively simple, undulating plane dipping in toward the ultrabasic mass at an angle of about 75°. The map relations also suggest that the monzodiorite mass has cut out a part of the border zone of the complex, for a conspicuous band of hornblendite bordering the complex at Cape Strait wedges out along the contact with monzodiorite near Kane Peak. The evidence for the later intrusion of the monzodiorite is however notconclusive. A border zone of hornblendite is not present along other observed contacts of the complex, and the quartz diorite dike may be younger than either the monzodiorite mass or the complex. However, such as the evidence is, it points to the conclusion that the monzodiorite is the younger of the intrusive masses. The change in mineralogy and composition of the monzodiorite near its contact with the ultrabasic rocks must be ascribed, as Buddington has suggested, to reaction of the monzodiorite magma with the ultrabasic rock. The ultrabasic rock seems to be little changed near the contacts with the monzodiorite except for a tendency for biotite to be more abundant.

Perhaps the sporadic appearance of biotite elsewhere in the peridotites of the complex and locally in considerable abundance, can be ascribed to the action of solutions emanating from the monzodiorite intrusion.

Structure

A number of observations indicate that the contact between the Kane Peak complex and the surrounding rocks dips inward centripetally on all sides. The best exposure that has been observed of the contact of the peridotite with enclosing rocks is at the base of the remnant of wehrlite and lehrzolite that forms the southernmost outcrop of the complex. Here the rock of the complex forms an east-west-trending ledge along a steep north to northeast-facing slope. The dip of the contact between the ultrabasic rocks and the underlying hornblende gneiss may be seen in several places along this ledge to be about the same as the inclination of the slope, so that the hornblende gneiss passes beneath the ultrabasic rock on the up-hill side of the ledge and reappears again below the ledge where the stream has cut down through the ultrabasic rocks. The contact is thus revealed over a vertical distance of about 300 feet to dip inward at an angle of about 40°. A high-angle fault downthrown on the north separates this outcrop from the rest of the complex, and on the north side of the fault the base of the complex has been dropped below the present level of exposure.

The structure of the complex may also be inferred from the contact between the marginal olivine augitite mass forming the shoulder of Kane Peak and the central mass of dunite, augite dunite, and wehrlite. This contact forms a sinuous line about a mile long within the mapped area of the complex. At several localities along this contact it is well enough exposed to permit direct observation of its attitude, and it is seen to dip in toward the dunite core at angles ranging from 30° to 58°. The sinuous trace of this contact upon the present surface is due to the fact that the contact surface and the east-facing slopes of Kane Peak are inclined at the same general attitude so that small deviations in either surface produce considerable irregularity in the position of the contact on the map.

Map relations and one direct observation indicate that the contact of the complex with the monzodiorite mass on the shoulder of Kane Peak dips southeastward toward the ultrabasic mass about 75°. The monzodiorite mass has been shown to be probably younger than the complex and possibly to have cut out a part of the complex along this contact, but the attitude of the contact may have been partly controlled by the original contact between the complex and the rocks it invaded. Some evidence for this supposition is seen in the fact that bands of wehrlite within the olivine augitite near the monzodiorite contact parallel the contact.

At Cape Strait the bedding in the metagraywacke near the contact and an indistinct banding in the hornblendite of the complex both dip southeastward about 80°, which suggests that the contact here has about the same attitude.

Near the contact of the complex with granulitized phyllite at the south end of the exposures along the shore of Frederick Sound there are a number of places where the wehrlite and olivine augitite has a slight but distinct layered or banded aspect. This banding dips northwestward from 30° to 50°.

All the observation that have been made indicate that the complex is funnel-shaped at the present level of exposure. The contacts probably dip inward all around the complex at angles ranging from 30° to 80°. The contacts along the southern and western margins of the complex are apparently somewhat less steeply inclined, ranging from 30° to 50° in dip, while the rather inconclusive observations along the northwestern border of the complex indicate an inward dip of the contact of between 70° and 80°. It also appears that the attitude of the bedded rocks in which the complex is emplaced tends to swing into conformity with the contact all around the complex.

Some complications in the structure of the complex are presented by the large mass of olivine augitite at the western end of the complex. Within the olivine augitite mass there are numerous thin layers or bands of wehrlite and augite dunite. In a general way these olivine-rich bands in the rock have a synclinal arrangement, the axis of which plunges eastward toward the center of the complex. The bands of olivine-rich rock dip southeastward near the contact between the complex and the monzodiorite mass, they flatten and dip eastward just below the small summit enclosed by the 2,800 foot contour on the shoulder of Kane Peak, and southeast of this summit the bands of olivine-rich rock swing to a northwesterly dip of about 65°. If these bands reflect the underlying configuration of the floor of the complex, they suggest that the olivine augitite mass, which is such a conspicuous feature at the western end of the complex, occupies a sag in the eastward-plunging floor of the complex. The sag or trough in the floor causes the outline of the complex at the present surface to bulge to the southwest. Apparently during the crystallization of the complex the conditions in this part of the chamber were particularly favorable for the formation of a wide border zone of coarse olivine augitite.

In addition to the bands or layers of wehrlite and olivine augitite that have a more or less regular synclinal arrangement, there are other dike-like bodies of augite dunite and wehrlite in the olivine augitite. Some of these bodies exhibit a streaky or banded structure owing to the presence of greater or lesser amounts of augite in streaks or bands parallel to the walls of the bodies. The augite is in coarse, detached crystals that are later than the olivine and enclose olivine grains poikilitically. The augite is not in aggregates or masses. These bodies are interpreted as true dikes derived from the inner part of the complex before its complete crystallization, and the streaky distribution of augite is probably a flow structure.

Aside from the high-angle fault along the south edge of the complex and a few shear zones noted here and there in the complex, the complex does not appear to have undergone sufficient deformation subsequent to its emplacement to materially alter its original internal or external structural relationships. Apparently no strong disturbances accompanied the intrusion of the adjacent stock of monzodiorite. The folding and metamorphism of the adjoining sedimentary rocks appears to have been completed before the intrusion of the ultrabasic mass.

Contact metamorphism effected by the complex on the surrounding rocks has been superimposed on a preexisting regional metamorphism.

Discussion and comparison with the Blashke Island complex

The rocks and their petrologic and chemical relationships are much the same in the Kane Peak and the Blashke Island complexes despite the differences that have been noted. The most important differences are in the degree of contact metamorphism produced by the two complexes and in their structural relations with enclosing rocks. Contact metamorphism and the consequent development of a gabbroic border zone is much less intense around the Kane Peak complex. The Kane Peak complex has been rather definitely established as having funnel-shaped, inward dipping contacts with enclosing rocks, and the Blashke Island complex is surmised to be a steep-walled cylinder that, if anything, passes into a steep domal structure near the present level of exposure. Nevertheless both masses consist of a core in which forsteritic olivine is the major phase and outer zones in which augite becomes increasingly abundant to the point of becoming the major phase. In both complexes the major phases exhibit cryptic zoning in composition, and the pattern of cryptic zoning is closely parallel.

There can be little doubt that the genetic processes operating in both complexes were essentially the same and that the differences between the complexes are due to local variations in the conditions under which the genetic processes operated. The structural differences in the two complexes effectively eliminate a common genetic process in which the external structure of the complex is a major factor. For example, the origin of the Blashke Island complex through a process of fractional crystallization and the settling out of the earlier phases was discussed and rejected because it did not explain the concentric, steep-walled configuration of the complex. The configuration of the Kane Peak complex makes it all the more necessary to dismiss this hypothesis from consideration because the augitic border zones of the complex underlie the olivenic core, and if crystal settling had operated to produce the complex, augite would have had to crystallize first and settle through an olivine-rich liquid. This contravenes physical-chemical and petrographic knowledge of the sequence of crystallization of these two phases. Furthermore the cryptic zoning in the composition of augite and olivine puts the more iron-rich and lower temperature members of both isomorphous series at the base of the Kane Peak complex with the more magnesian, higher temperature olivine and augite higher up in the complex toward the core. This is the opposite of the relationships found in stratiform complexes in which crystallization differentiation has been most clearly demonstrated to be the effective genetic process.

The same objections that have been applied to other methods of origin in the discussion of the Blashke Island complex apply with equal force to the Kane Peak complex, and the ring dike hypothesis is rendered even more untenable by the centripetal dip of the floor of the Kane Peak complex. The ring dike mechanism calls for outward dips of the intrusive contacts.

The essential feature that the two complexes have in common is the relationship of rock types and mineral composition to the intrusive contact, and this relationship is shown to be independent, at least to a very substantial degree, of the attitude of the intrusive contact. Thus a process is called for that is related to the contact in a way that is substantially independent of its attitude. The hypothesis that has been outlined to explain the Blashke Island complex, involving both diffusion of components along temperature and concentration gradients and the bulk migration of components in solution owing to a building up of fluid concentration in the cooler regions of the complex, is the best that the present author can offer to explain the essential features that both complexes have in common.

It now remains to explain the important differences between the Kane Peak complex and the Blashke Island complex in terms of the hypothesis of origin that has been offered. The really significant difference is the absence of an extensive gabbro ring and a broad zone of intense thermal metamorphism around the margins of the Kane Peak complex. Two reasons for this difference can be offered.

The first is based on the structural differences in the two complexes, and is that the outward migration of solutions and the possible interchange by diffusion that has been called upon to explain the gabbroization of the rocks surrounding the Blashke Island complex may have had a strong upward as well as outward component, thus the walls of the Kane Peak complex, flaring away from the lower sources of fluids and thermal energy, would escape the effects to some degree. It is perhaps significant in this connection that the thick hornblendite marginal zone, which probably approaches gabbro in bulk composition, is located along the steep-walled side of the Kane Peak complex.

The Kane Peak complex and the Blashke Island complex may expose different levels of very similar ultrabasic intrusions. The Kane Peak complex may expose a section near the floor, and the Blashke Island complex a section near the middle or toward the roof, of bodies that were essentially globular masses in their entirety. But the Kane Peak complex may pass downward into a feeding conduit that extends to plutonic depth, and the Blashke Island complex may extend downward indefinitely without a basined floor. The suggestion of globular form is nothing more than a suggestion and is not essential to the hypothesis of differentiation that has been offered.

The second suggestion that can be offered may combine with the first to explain the lack of extreme thermal metamorphism around the Kane Peak complex. The Kane Peak intrusion may have not had as much thermal energy as the Blashke Island complex when it came to rest in the place in which it finally solidified. the magma may have lost more heat and volatiles in reaching its final position and thus contained a higher percentage of crystalline material in suspension at a lower temperature. The process of differentiation would therefore not have been carried to the degree of perfection seen in the Blashke Island complex. A large dunite core substantially free of augite would not so readily form and the outer sone of augitite would not be so wide and perfect. Certain peculiar contact facies of the peridotite such as the biotite lehrzolite porphyry might be the result of partial chilling and arrested reaction along the margins of the complex.

On the whole it appears that the differences in the Blashke Island and Kane Peak complexes can best be explained in terms of the influence of structural differences at the respective levels at which the two intrusions are exposed on an essentially identical process of differentiation. In this author's not altogether impartial view, a comparison of the complexes adds support to the hypothesis of differentiation that he has offered to explain them. The Kane Peak complex merits further detailed study.

Notes on the Mount Burnett complex

The Mount Burnett complex is a composite mass of dunite, wehrlite, augitite, hornblendite, and gabbro lithologically similar to the Blashke Island and Kane Peak complexes. The composite mass is about 7 miles long and 1 to 2 miles wide and extends from the east shore of Union Bay on Cleveland Peninsula eastward to within a few thousand feet of Vixen Creek at the head of Vixen Inlet. An unknown, but probably minor part of the complex is concealed beneath the waters of Union Bay. A view across the Mount Burnett complex is shown in plate 4.

Buddington published a brief petrographic description of a facies of the augitite present along the shore of Union Bay (Buddington and Chapin, 1929, pp.193-4). George C. Kennedy and the present author have described the exposures of the complex along the shore of Union Bay at the western end of the complex and on Mount Burnett at the eastern end of the complex (Kennedy and Walton, 1946, pp. 80-83). A few days were allotted at the close of the season during which the present investigation was made to reconnoiter the central part of the complex between Union Bay and Mount Burnett in the hope that some additional observations here would establish the essential structural outlines of the complex and afford a basis for comparison with the better known Blashke Island and Kane Peak complexes. The central part of the complex forms a precipitous ridge ranging in altitude from about 2,000 to about 3,000 feet and unfortunately the reconnaissance of this area had to be carried out for the most part during a prolonged storm that reduced visibility to a few yards and made effective mapping all but impossible. Therefore the geologic map published by Kennedy and Walton (1946, plate 22) is reproduced here as figure 19, page 228, with a few revisions and additions. The present account summarizes some of the previous investigations, adds a few additional observations, and makes some limited comparisons with the Blashke Island and Kane Peak complexes.

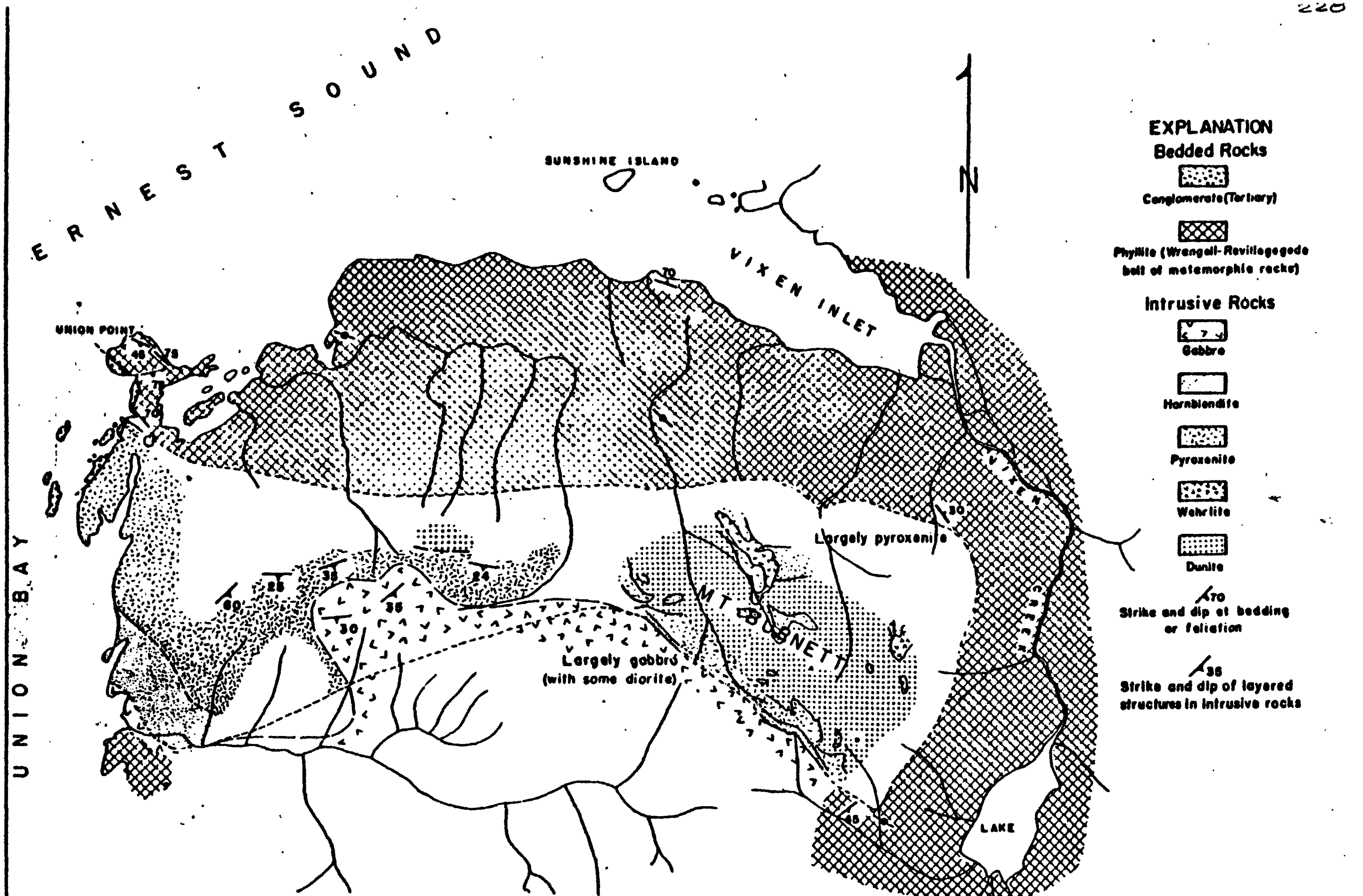

Figure 19. GENERALIZED GEOLOGIC MAP OF MT. BURNETT AND VICINITY, SOUTHEASTERN ALASKA

Geology by George C. Kennedy and Matt S. Walton, Jr., 1943
Revised by Matt S. Walton, Jr., 1951

The Mount Burnett complex is, in many of its essential features, very similar to the Blashke Island and Kane Peak complexes, although there are major structural differences. The major rock units of the Mount Burnett complex are, as in the other complexes, dunite, augite dunite, wehrlite, olivine augitite, hornblendite, and gabbro. Some minor variants not noted in the other complexes are; augitite or diallagite, free of olivine and characterized by abundant accessory ilmenite and some spinel, small segregations of chromite ranging from clusters of a few chromite grains up to a mass estimated to contain about 25 tons of massive chromite, and thin bands up to an inch or two thick of ilmenite and magnetite.

The contact relations between the major rock units are in all respects similar to the contact relations between analogous units noted in the other complexes, and it is important to note that although the Mount Burnett complex is several times longer than its average width, in contrast with the more or less circular plan of the other complexes, the olivine-rich rocks form the internal elements of the complex and are rimmed by successive shells of progressively more siliceous and less magnesian rock, wherever a sequence from the interior of the complex outward has been observed. Kennedy states, "At every place where contact relations were observed, pyroxenite of the marginal zone was bordered on the outer side by hornblendite. At no point was dunite noted in contact with hornblendite, nor was dunite or pyroxenite in contact with the surrounding schists and phyllites of the Wrangell-Revillagigedo belt of rocks." (Kennedy and Walton, 1946, pp. 81, 82.)

The structure of the Mount Burnett complex is most inadequately known except for the fact that olivine-rich rocks forming the internal elements are rimmed by successive shells of pyroxenite, hornblendite, and gabbro. In the vicinity of Mount Burnett irregular masses of wehrlite and olivine augitite are present well within the main mass of dunite and it is conceivable that these represent roof pendants of an irregular shell of pyroxenite that has been largely eroded from over the dunite. The reconnaissance carried out during the present investigation shows that in the central part of the complex, between Mount Burnett and Union Bay, dunite is overlain by successive layers of olivine augitite and gabbro with moderate southerly dips from the center of the complex southward. A section from south to north part way across the complex near its center gives the following sequence; gabbro with a strong gneissic structure dipping in a southerly direction 30° to 35°, olivine augitite with streaks of wehrlite and augite dunite dipping in a southerly direction 25° to 35° (see plate 15), dunite with streaks of augite dunite and wehrlite dipping conformably with the overlying olivine augitite. No observations have been made that give any indication of what the structure is north of the dunite at the base of this sequence, although it is known that pyroxenite is present along the northern margin of the complex and around the eastern end. Two possibilities suggest themselves; either the southward dipping layered structure continues and the pyroxenite underlies the dunite, or the dunite is the core of a domal structure and the pyroxenite overlying the dunite arches over the dunite and reverses to a northerly dip along the northern borders of the complex. The overall structure of the complex, as now envisiaged on the basis of incomplete information, is that of a steep-sided, roughly domal mass of dunite with successive shells of pyroxenite, and hornblendite or gabbro, or both, in the area of Mount Burnett. This core of dunite narrows to the west and passes beneath a roof of pyroxenite and gabbro as an elongate, plunging, domal body, or else the dunite passes into a tabular, sill-like mass extending to the west and tilted to the south, both overlain and underlain by pyroxenite and gabbro.

Perhaps it is premature to make any generalizations about the Mount Burnett complex on the basis of inadequate information, but enough is known to make it certain that whatever the structure may be, it is different in important respects from both the Blashke Island and Kane Peak complexes. In the Blashke Island complex the contacts between successive shells of the complex and with the enclosing rocks are essentially vertical. In the Kane Peak complex the contacts dip inward all around the ultrabasic mass, and the outer shells underlie the dunite core. In the Mount Burnett complex there is adequate evidence to show that in some places the outer shells of the complex overlie the dunite. Thus, the Mount Burnett complex gives further support to the view that the process of differentiation by which these complexes came into being is to a considerable extent independent of structure.

It has been suggested that the lesser development of a gabbroic outer zone and the lesser intensity and extent of granulitic contact metamorphism in the enclosing rocks of the Kane Peak complex as compared with the Blashke Island complex are due to the enclosing rocks dipping beneath the Kane Peak complex at moderate to high angles. In contrast it is notable that there is a well developed gabbroic shell in the Mount Burnett complex in the places where the outer shells overlie the core of the complex. At the south end of the exposures of the rocks of the Mount Burnett complex along the shores of Union Bay, particularly striking evidence may be seen for the gradation of hornblendite into gabbro and gabbro into granulitized schist and phyllite over a distance of several thousand feet.

The fragmentary evidence provided by present knowledge of the Mount Burnett complex suggests that the genetic process was similar to that in the Blashke Island and Kane Peak complexes, modified by differences in the structural configuration assumed by the intrusion at the present level of exposure.

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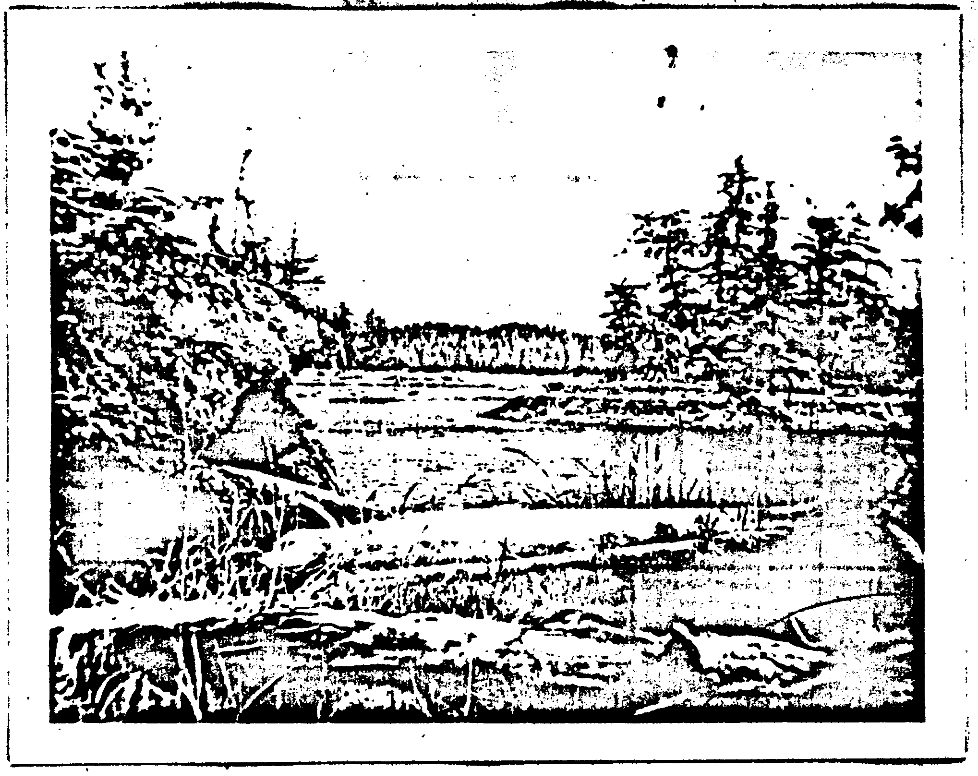

Plate 2, View across central lagoon area of Blashke Islands toward the east. The tide is at a moderately low stage exposing about 15 feet of bare rock up to high tide line. Inshore relief is low, the forest cover is thick, and rock exposures are poor. High mountains in far background are on Etolin Island.

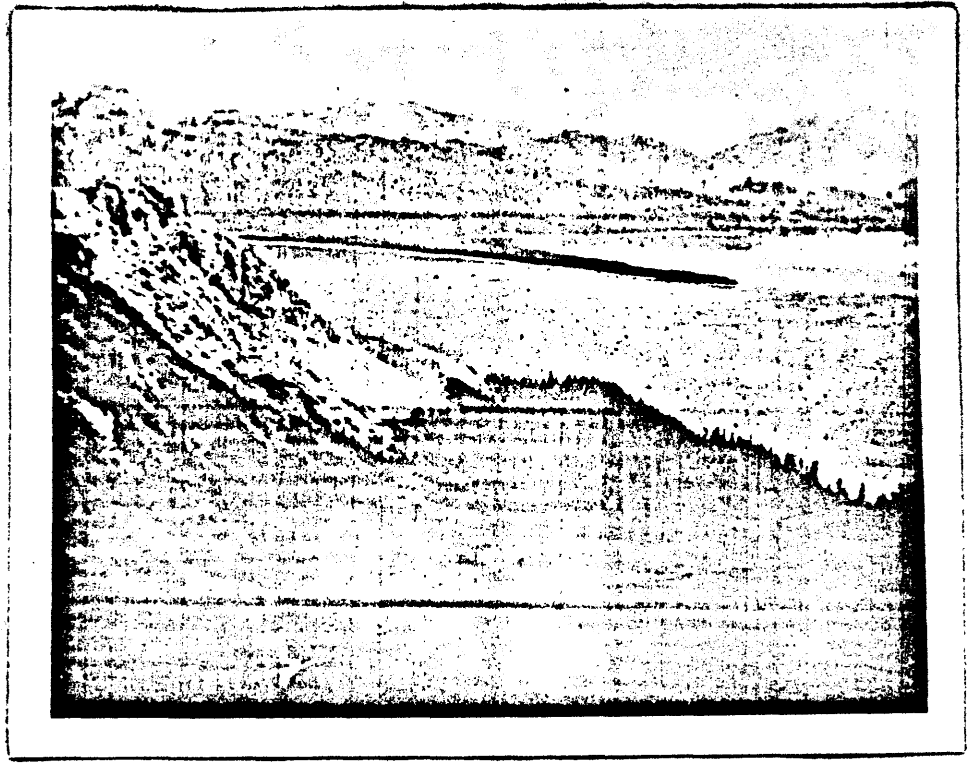

Plate 3, View northeastward across part of the Kane Peak ultrabasic area, Kupreanof Island. Kane Peak is at the left. The bare rock mass exposed in the center is composed of olivine augitite, wehrlite, and augite dunite. The large body of water in the background is Frederick Sound. The mountains in the far distance are the Coast Range on the mainland. The white dot at the far edge of the lake is an 8 foot square tent.

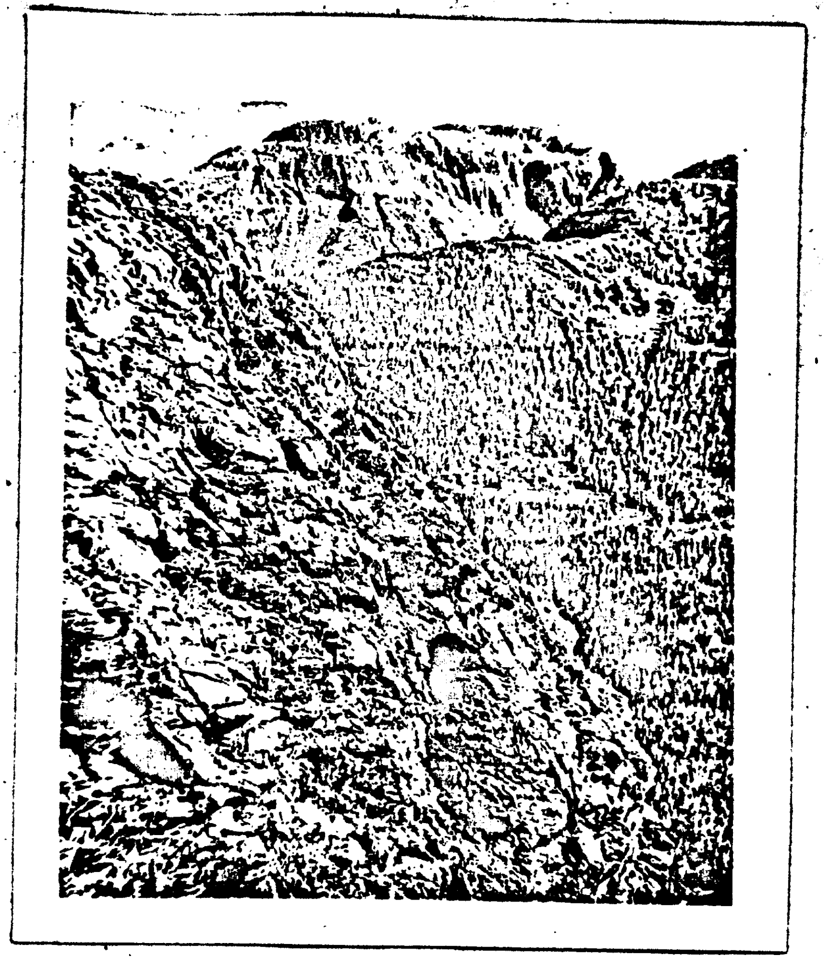

Plate 4. View eastward across the Mount Burnett ultrabasic area, Cleveland Peninsula. The rocks in the foreground are mainly olivine augitite with thin layers of wehrlite and augite dunite dipping southward about 30 degrees. The bare rock mass in the background is Mount Burnett, consisting mainly of dunite.

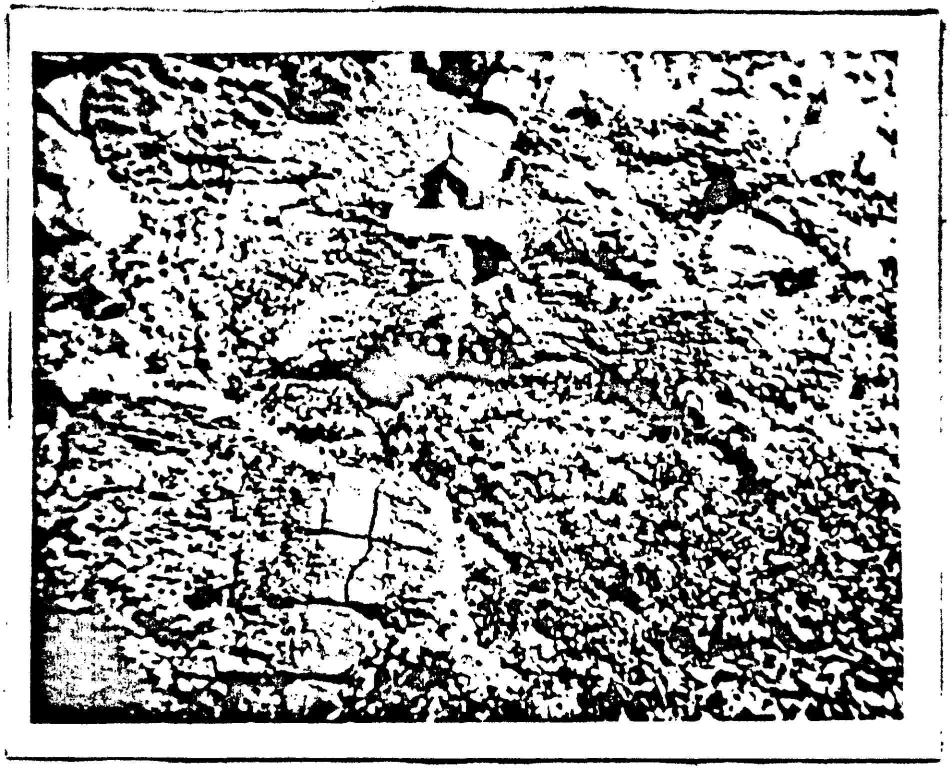

Plate 5, Augite dunite dike about 4 inches wide cutting sharply across coarse olivine augitite. The white material encrusted on the rock is barnacles. The dike, which weathers out in sharp relief is represented by specimen 133A, item 34, table 1. It consists mainly of olivine and serpentine derived from olivine with 5.9 percent of augite by volume.

Plate 6, Coarse augitite and olivine augitite dikes cutting massive dunite. This photograph was taken at the Mount Burnette area on Cleveland Peninsula, but similar features are well displayed on the Blashke Islands. Photograph by George C. Kennedy.

Plate 7, Coarse gabbroic pegmatite dike cutting olivine augitite. The dike rock consists of coarse anorthite (An96) with minor augite, hornblende, and other mafic minerals. Photograph by George C. Kennedy.

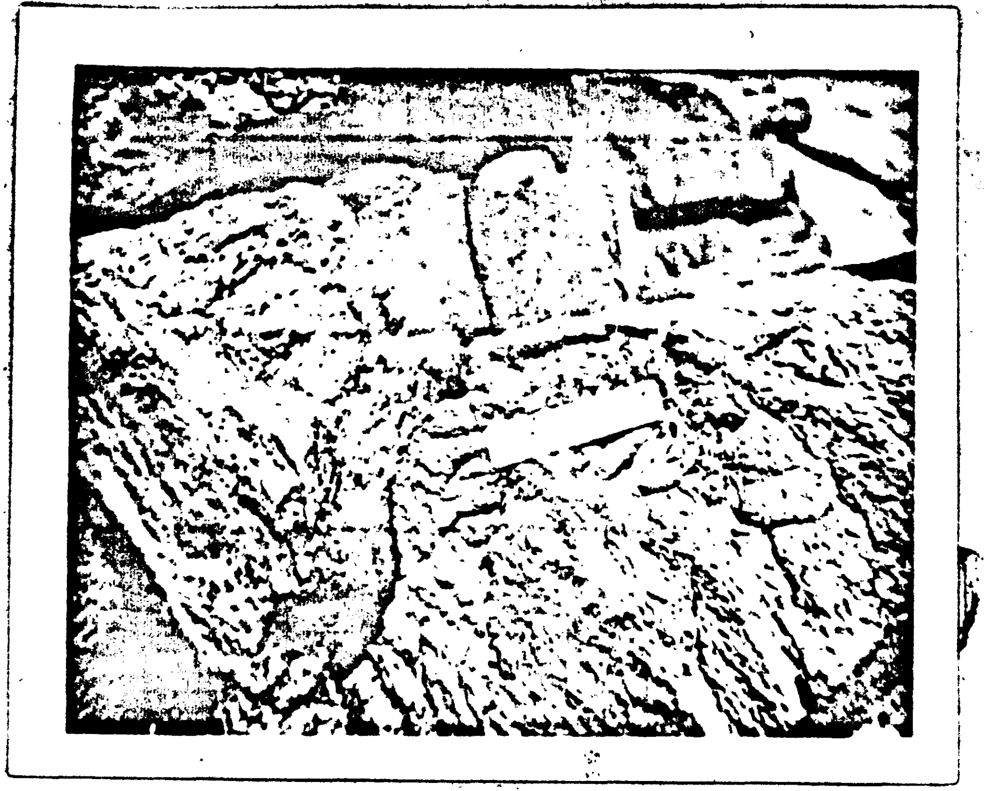

Plate 8, Small masses of coarse gabbroic pegmatite consisting mainly of anorthite (An93) with accessory olivine, augite, and hornblende. Specimen 335, item 99, table 1. These masses appear locally enclosed in coarse olivine augitite.

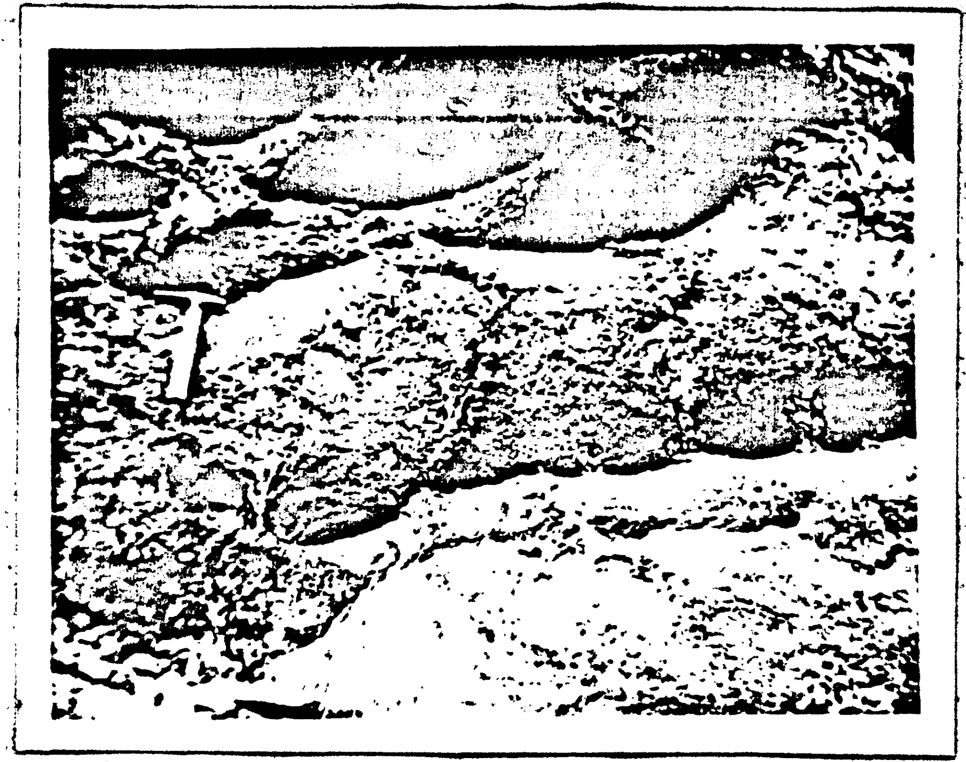

Plate 9, Irregular boxwork of coarse gabbroic pegmatite veins consisting of coarse anorthite and augite in about equal amount cutting coarse, massive olivine augitite. This locality is at the Kane Peak ultrabasic area on Kupreanof Island, but similar features are displayed on the Blashke Islands. Photograph by George C. Kennedy.

Plate 10, Banded gabbro showing a pattern of sweeping curves intersecting and converging at small angles. This structure is formed by the concentration of late hornblende in bands and streaks through the rock. A nearly vertical joint surface forms a step in the outcrop about three quarters of the way toward the top of the picture just below the six inch rule shown for scale. This vertical exposure shows the dip of the structure which is steep, approximately 75 degrees.

Plate 11, Banded gabbro exposed on a nearly vertical surface showing a steeply dipping set of curving bands transected by another set of less steeply dipping bands. The banding is formed by the concentration of late hornblende in layers and streaks through the rock. Pure white streaks and patches obscuring some of the banding are clusters of barnacles. Photograph by George C. Kennedy.

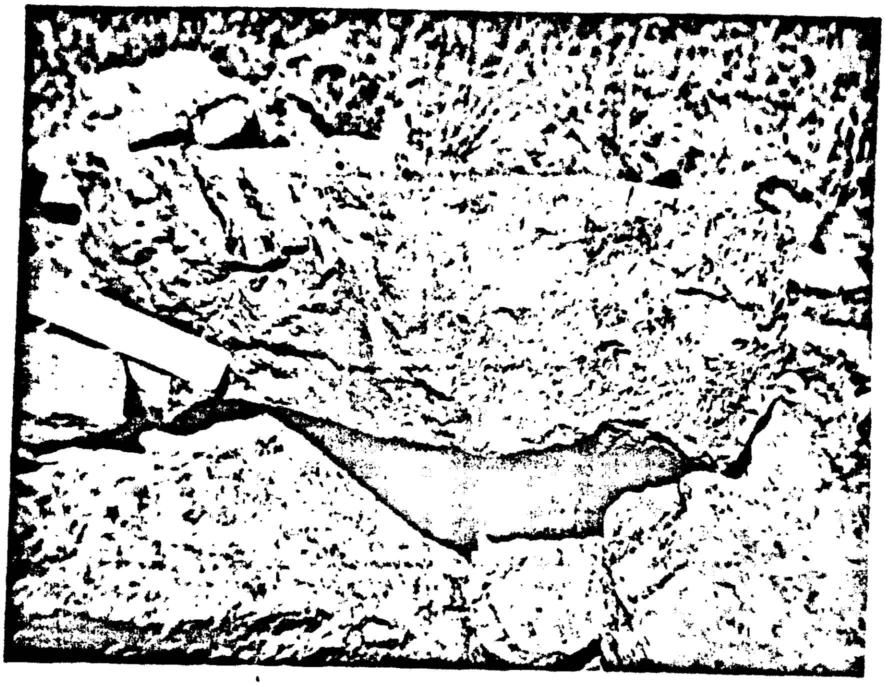

Plate 12, Intrusion breccia at a contact between gabbro and hornfelsed country rock. The lighter-colored gabbro encloses and veins numerous angular blocks and fragments of hornfelsed country rock.

Plate 13, Coarse gabbro containing numerous rounded to angular inclusions of country rock that have been metamorphosed to a hornblende-rich augite-plagioclase granulite. A mafic dike of the beerbachite group cuts both inclusions and gabbro. The dike has approximately the same mineralogy and composition as the granulite inclusions.

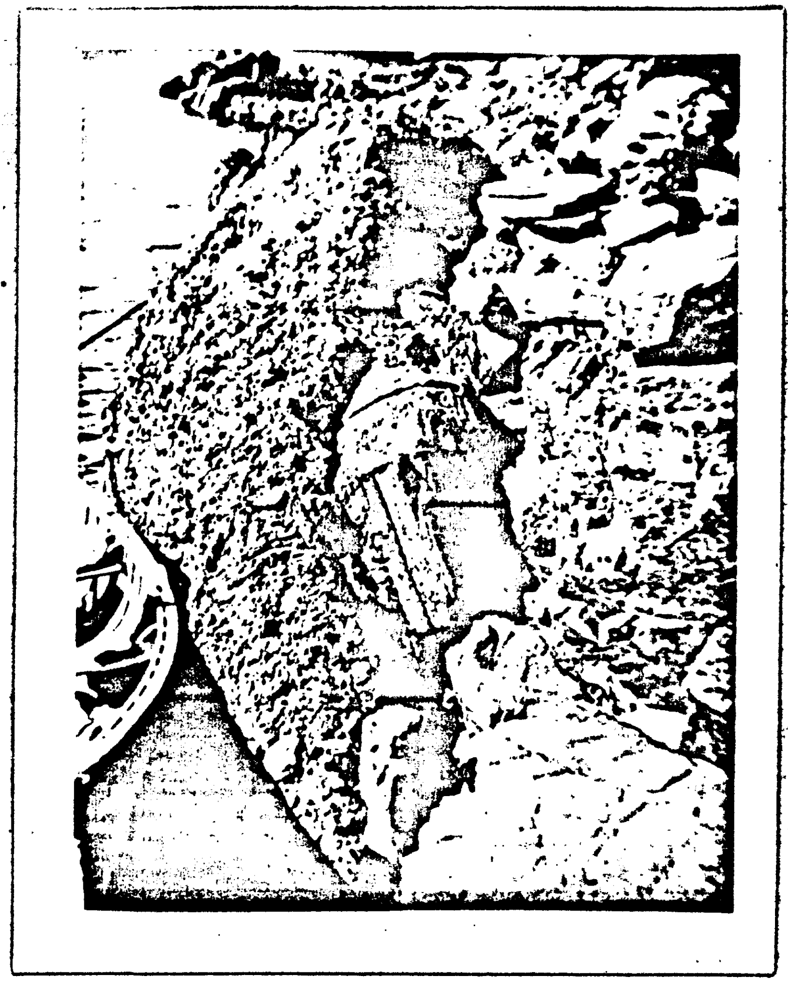

Plate 14, Fault breccia consisting of fragments of dunite and augite dunite in a matrix of pulverized and serpentinized peridotite. This breccia was produced by faulting along the western and southwestern borders of the peridotite mass. The faults and shear zones are in general steeply dipping. The geologic relationships show up to more than a thousand feet of horizontal displacement. Slickensides in some fault zones have strong vertical components and vertical displacements of the order of magnitude of the horizontal displacements may have taken place.

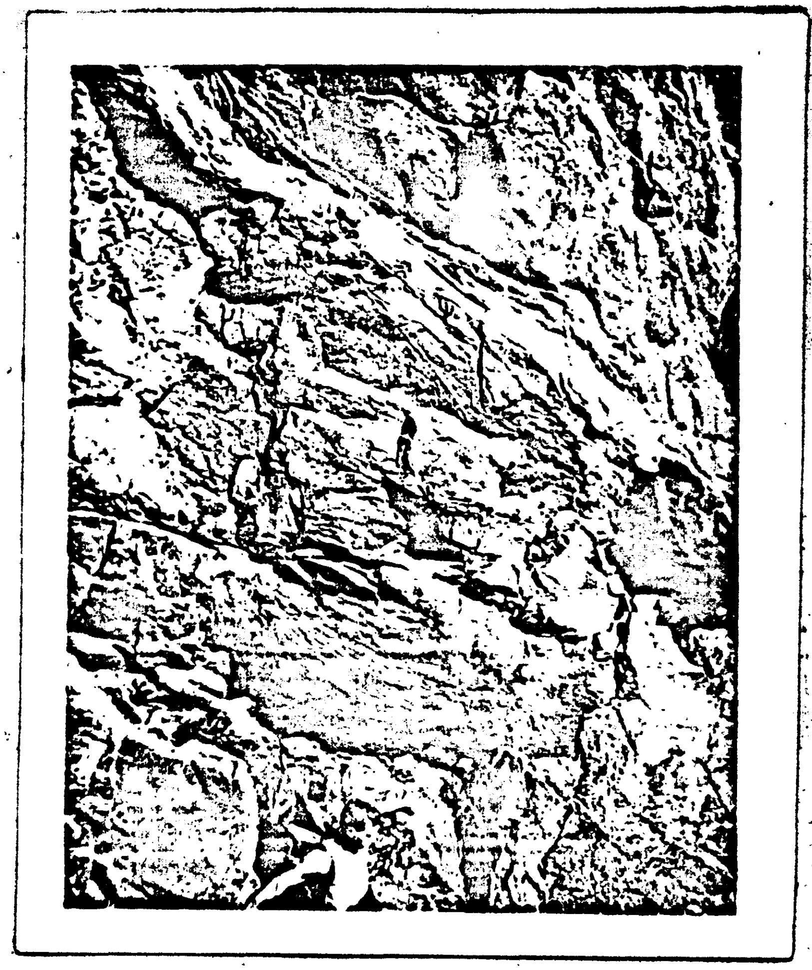

Plate 15. Vertical cliff of coarse olivine augitite near the center of the Mount Burnett complex containing thin layers of serpentinized augite dunite and wehrlite dipping about 30°. A layer of this kind cuts diagonally across the top of the picture from the upper left hand corner.

Plate 16A. Wehrlite containing poikilitic augite enclosing olivine grains in random orientation. The olivine shows traces of crystal form. Specimen 190, item 40, table 1. X30.

Plate 16B. A rounded grain of olivine enclosed in augite from olivine augitite. Specimen 137, item 76, table 1. X150.

Plate 17A. Hornblende pseudomorphs after augite enclosed in olivine. An unreplaced remnant of augite is shown at extinction in the strongly illuminated grain of hornblende. Specimen 261, item 80, table 1. ol = olivine, a = augite, h = hornblende. X150. Crossed nichols.

Plate 17B. Rounded grain of augite enclosed in olivine. Specimen 216, item 83, table 1, from olivine-poor augitite near the outer margin of the complex. X150. Crossed nichols.

Plate 18A. Primary hornblende of an unusual variety displaying pleochroism in brownish-pink to pale green enclosing grains of olivine in an uncommon facies of wehrlite. Specimen 133B, item 45, table 1. X20. Crossed nichols. ol = olivine, h = hornblende.

Plate 18B. Primary hornblende enclosed in olivine from olivine-poor augitite at the outer contact of the augitite with gabbro. Traces of graphic opaque exsolution lamellas may be seen in the olivine as described on page 51. Specimen 216, item 83, table 1. X50. Plane light. ol = olivine, a = augite, h = hornblende, and op = opaque exsolution lamella.

Plate 19A. Relatively fine grained dike of wehrlitic olivine augitite cutting augite dunite. The dike is only 1.8 mm wide but is continuous in outcrop for several meters. X30. Plane light. ol = olivine, a = augite, and s = serpentine.

Plate 19B. Olivine beerbachite dike containing olivine, and augite phenocrysts and hornblende poikilocrysts in an aplitic groundmass of granular olivine, augite, and plagioclase. ol = olivine, a = augite, p = plagioclase, and h = hornblende. Specimen 334, item 105, table 1. X30. Plane light. This dike cuts coarse olivine augitite.

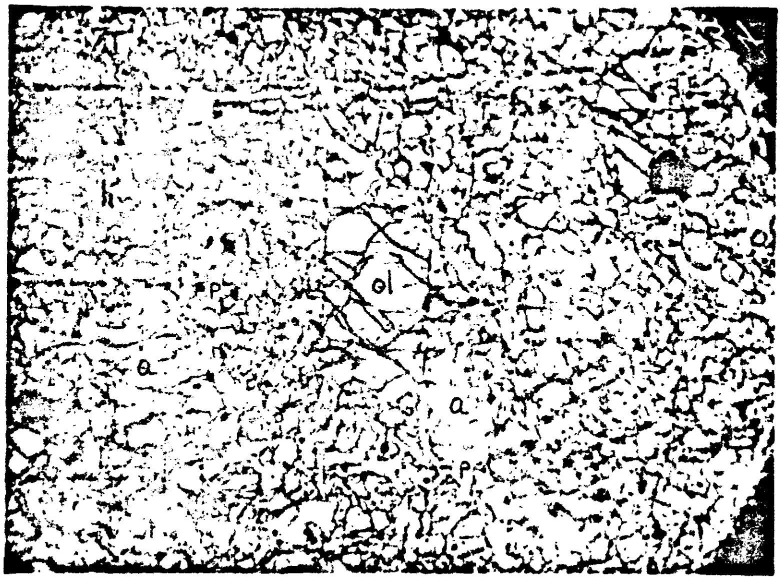

Plate 20A. Hornblendite beerbachite dike that cuts coarse olivine augitite. The dike consists of an aplitic aggregate of hornblende with a little interstitial plagioclase and minor amounts of augite and hypersthene. Specimen 99, item 112, table 1. Analysis, mode, and norm given in column P, table 2. X30. Plane light.

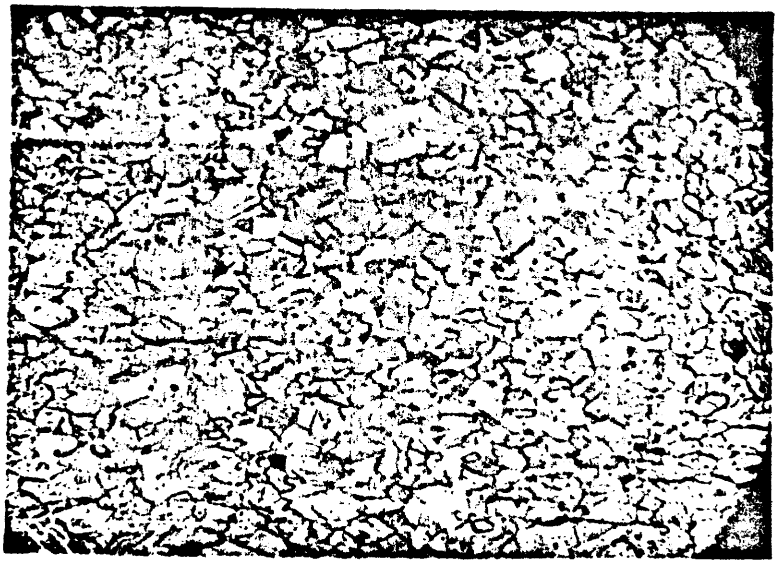

Plate 20B. Dike rock consisting of diopsidic augite and andradite garnet with minor penninite, cutting olivine augitite. a = augite, g = garnet, and cl = chlorite (penninite). Specimen 390, item 103, table 1. Analysis, mode and norm given in column M, table 2. X50. Plane light.

Plate 21A. Simple granulitic texture shown by a contact metamorphosed fossil, concretion, or amygdule in strongly metamorphosed country rock near direct contact with olivine augitite. p = plagioclase, a = augite. Specimen 280, item 157, table 1. X150. Plane light.

Plate 21B. Granulite from matrix of rock containing the relict shown in plate 21A. Relatively coarse poikilocrysts of iron-rich olivine (hyalosiderite) associated with biotite characterize this rock. Orthoclase is present along with plagioclase and augite. ol = olivine, bi = biotite, a = augite, p = plagioclase. Specimen 280, item 158, table 1. X150. Plane light.

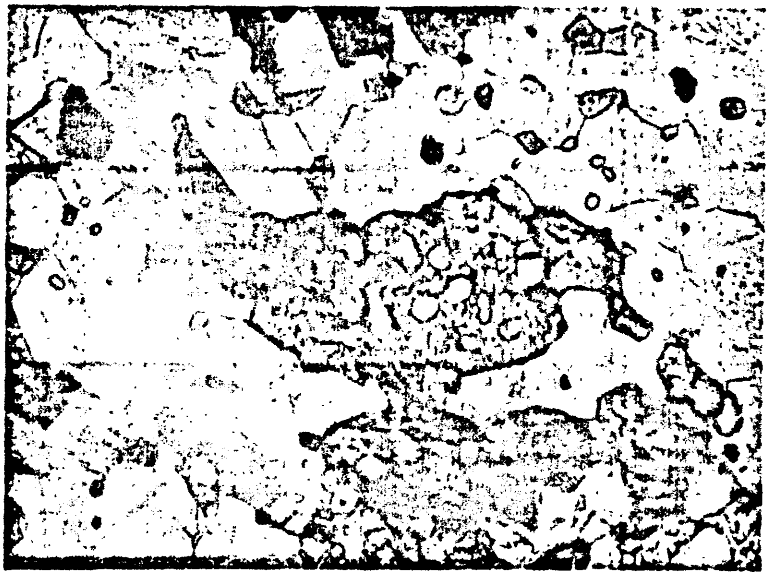

Plate 22A. Matrix of granulitized conglomerate in contact with a wehrlitic contact facies of the ultrabasic complex. ol = olivine (hyalosiderite), a = augite, bi = biotite, p = plagioclase, and ap = apatite. Specimen 368, item 162, table 1. X150. Plane light.

Plate 22B. Inclusion of country rock in olivine augitite. The inclusion has been converted into an aggregate of olivine, hypersthene, and hornblende with a little calcic plagioclase. ol = olivine, hy = hyperathene, h = hornblende. Specimen 284, item 143, table 1. X30. Plane light.

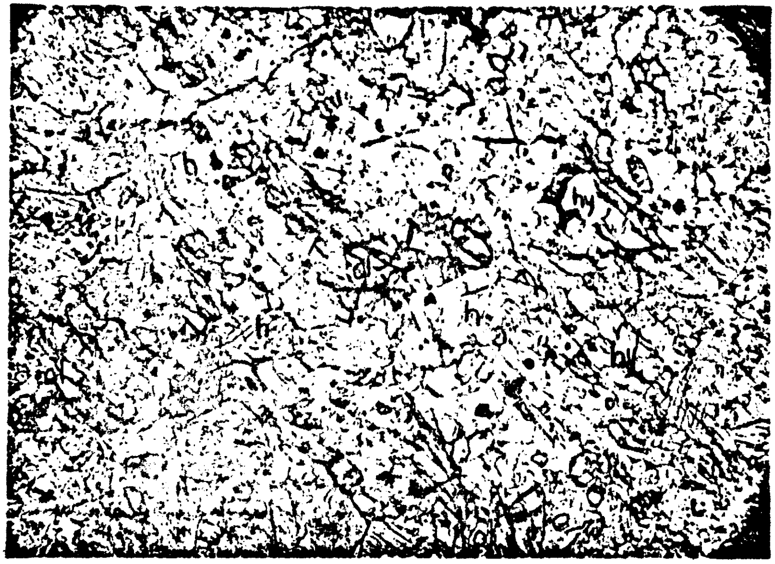

Plate 23A. Coarse poikilitic olivine enclosing hornblende and augite from an inclusion of country rock in a gabbroic streak within strongly granulitized country rock near a contact with peridotite. ol = olivine, a = augite, and h = hornblende. Specimen 358, item 145, table 1. X150. Plane light.

Plate 23B. Chromite crystal in typical serpentinized dunite. The serpentine shows a strong preferred orientation with the optical direction X perpendicular to the faces of the chromite crystal. c = chromite, ol = olivine, s = serpentine. Specimen 315, item 6, table 1. X150. Plane light.

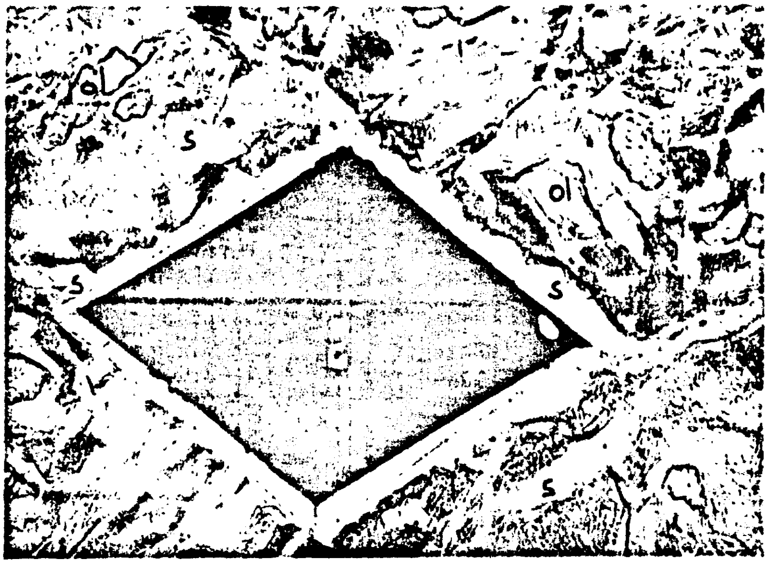

Plate 24A. Rounded grain of anorthite enclosed in olivine from olivine augitite. Specimen 216, item 83, table 1. X150. Crossed nichols.

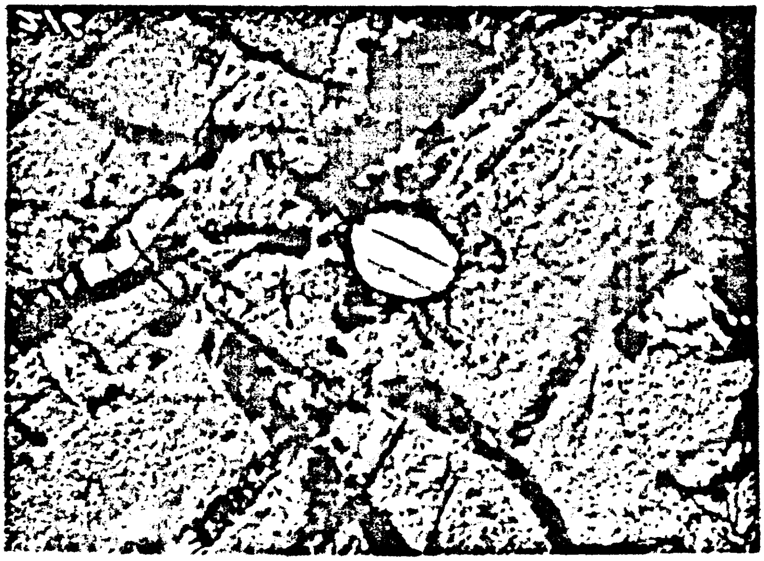

Plate 24B. Olivine partially enclosing anorthite with no trace of corona development from a coarse gabbroic pegmatite mass in olivine augitite Note the angle of pericline twinning against the 001 cleavage. X150. Crossed nichols. Specimen 244, item 100, table 1.

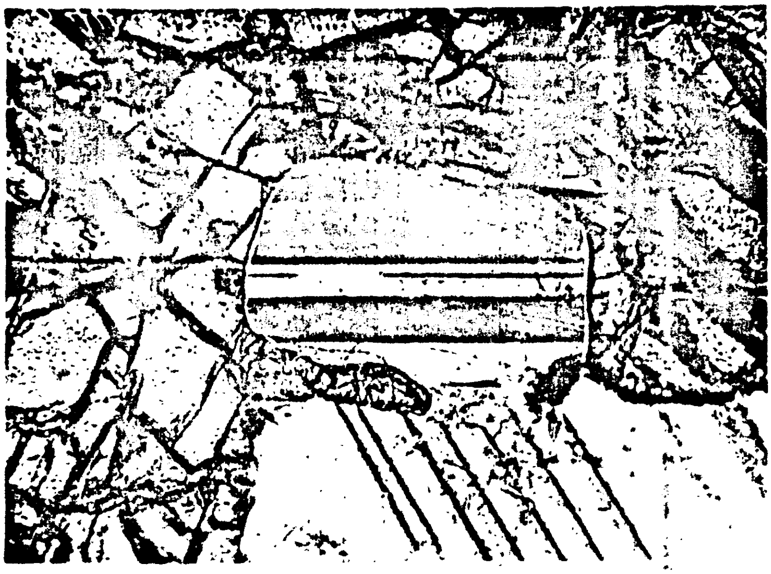

Plate 25A. Opaque exsolution lamella with a fine graphic pattern in a shattered and partially serpentinized grain of olivine. Lamella crosses the serpentinized fractures without interruption. X150 Plane light. A similar feature is seen in plate 18B.

Plate 25B. Olivine enclosed in coarse anorthite from a gabbroic pegmatite that also contains olivine enclosing anorthite. (Plate 24B). Specimen 244, item 100, table 1. X150. Plane light.

Plate 26A. Koswite, a rock consisting of olivine and augite in a sideronitic matrix of magnetite with a little pyrite. Specimen 410, item 95, table 1. X50. Plane light.

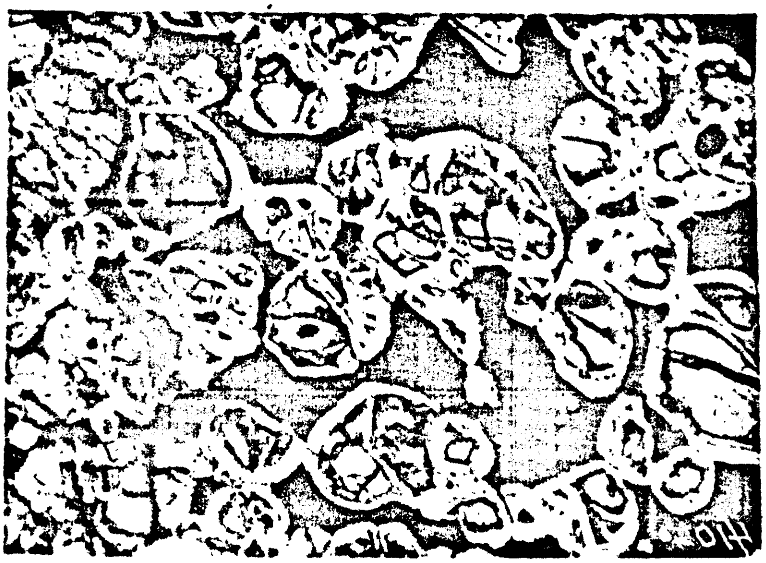

Plate 26B. Gabbro with coronas of pale amphibole surrounding both olivine and augite in contact with plagioclase. ol = olivine, a = augite, am = amphibole, and p = plagioclase. Specimen 220, item 120, table 1. X50. Plane light.

Plate 27A. Gabbro with coronas of pale amphibole surrounding olivine and augite in contact with plagioclase. Specimen 219, item 119, table 1. X30. Plane light.

Plate 27B. Gabbro with coronas similar to those in plates 26B and 27A. Specimen 308, item 122, table 1. X50. Plane light.

Plate 28A. Coarse olivine in gabbro with partial coronas of pale amphibole, hypersthene, and magnetite locally in a graphic intergrowth. The olivine is later than the plagioclase and contains inclusions of plagioclase. Specimen 142, item 118, table 1. X50. Plane light.

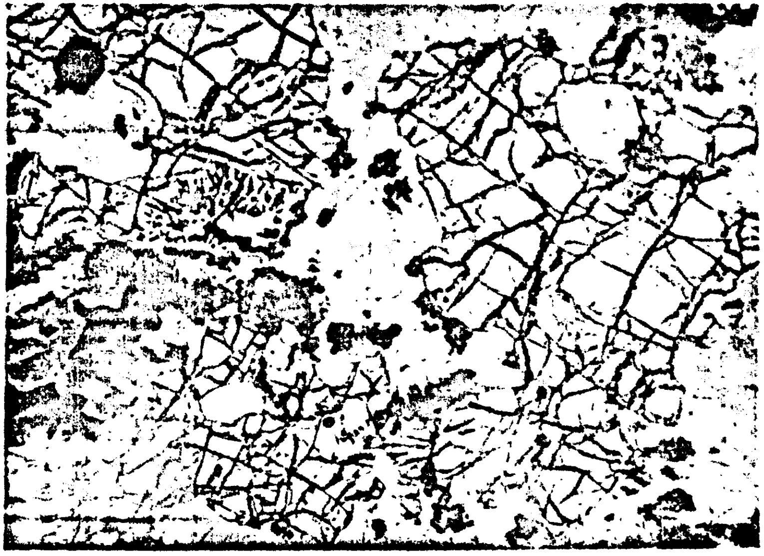

Plate 28B. Coronas of augite surrounding hypersthene enclosed in poikilocrysts of hornblende.

a = augite, hy = hypersthene, h = hornblende. Specimen 347, item 123, table 1. X150, crossed nichols.