A PETROLOGICAL STUDY OF THE CUTHBERT LAKE ULTRABASIC AND BASIC DYKE SWARM; A COMPARISON OF THE CUTHBERT LAKE ULTRABASIC ROCKS TO THE MOAK LAKE-TYPE SERPENTINITE

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by

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ABSTRACT

In the Thompson Lake-Moak Lake area of northern Manitoba, two types of ultrabasic rocks occur. Serpentinite at Moak Lake is situated along a structural break running from Split Lake to Setting Lake. Ultrabasic rocks in dyke form occupy a pronounced lineament in the vicinity of Cuthbert Lake. Associated with the ultrabasic dykes is a basic dyke swarm. The purpose of this study is two-fold: to examine the ultrabasic and basic dykes of the Cuthbert Lake area, and to compare the two types of ultrabasic rocks to find the relationship between them. An explanation is sought for the fact that economic nickel sulphide deposits are associated with the Moak Lake type of ultrabasic rocks and not with those of Cuthbert Lake.

A part of the Thompson Lake-Moak Lake area, including the Cuthbert Lake area, was mapped during the 1958 field season. A review of a portion of the literature of ultrabasic rocks was undertaken to form a background for the problems connected with these rocks. Thin sections of specimens of the ultrabasic and basic dykes of the Cuthbert Lake area, plus two chemical analyses of these rocks were used to ascertain their petrological relationship. The structural relationships of these dykes and their relationships to the enclosing rocks were studied both in the field and by Schmidt-net and stereographic net techniques. The

International Nickel Company supplied the writer with a cross section of drill core samples of the Moak Lake serpentinite body. Thin sections and polished sections as well as a representative chemical analysis of this rock provided material for a comparison with the Cuthbert Lake ultrabasic dykes.

As a result of this study, it is concluded that the rocks similar to the Moak Lake type of ultrabasic rock are Alpine-type peridotite, and that they were intruded during a period in which an island arc system occupied the area. The Cuthbert Lake ultrabasic and basic dykes, on the other hand, are found to represent different phases of a differentiated basic magma.

A feasible explanation for the restriction of economic nickel sulphide deposits to the Moak Lake type of ultrabasic rock is presented in a discussion of the different geological processes through which these rocks have passed.

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CHAPTER I

INTRODUCTION

GENERAL STATEMENT

Important nickel-bearing sulphide deposits have recently been found associated with ultrabasic serpentinite bodies in the Thompson Lake - Moak Lake area of northern Manitoba. In the vicinity of Cuthbert Lake, which lies within the Thompson Lake-Moak Lake area (see figure 1), an ultrabasic dyke and an associated basic dyke swarm form an important part of the lithology. However, economic nickel deposits have not been found associated with these latter rocks.

The purpose of this study is to examine the relationship between the basic and ultrabasic dykes of the Cuthbert Lake area, and to compare the ultrabasic rocks of this region with the nickel-bearing ultrabasic rocks in the vicinity of Moak Lake. An explanation is sought for the fact that nickel ore deposits are associated with one group of ultrabasic rocks and not with the other.

PREVIOUS GEOLOGICAL WORK

The following summary of the early geological history of the area has been taken from Dawson's report (1952).

The earliest geological work in the Thompson Lake-Moak Lake area was done in 1896 by J. B. Tyrrell of the Geological Survey of Canada. He followed the canoe route from Sipiwesk Lake through Landing, Wintering, Paint, and Ospwagan lakes, and ascended the Burntwood River to Nelson House. His report gives a brief description of the rock types encountered in the southern and western parts of the area.

During the summer of 1906, William McInnes, also of the Geological Survey of Canada, descended the Nelson River to Split Lake and proceeded west up the Burntwood River. He reported the presence of greenstone along the lower part of the Burntwood River.

Another Geological Survey of Canada party, led by F. J. Alcock, mapped the Ospwagan Lake area in 1920 and outlined a greenstone belt extending north to the Burntwood River.

The years 1928 and 1929 marked a period of mineral exploration in the area. This resulted in the discovery of several prospects, chiefly of base metals. In connection with this activity, J. F. Wright of the Geological Survey of Canada travelled down the Grass River from Wekusko Lake to Thicket Portage during the late summer of 1930. In the

course of this trip, he examined the geology and mineral prospects of Paint, Ospwagan, Mystery, Partridge Crop, Natawahunan, Wintering, and Landing lakes.

A. S. Dawson, in the summer of 1941, mapped the area bounded by longitudes 96°45' and 98°15' west and latitudes 55°15' and 56°07'30'' north for the Manitoba Department of Mines and Natural Resources. This work, published in 1952 under the title "Partridge Crop Lake Area", was done in one summer. The area surveyed by F. J. Alcock in 1920 was not re-done, but was incorporated into Dawson's work, which was published on a map at the scale of one inch to two miles.

During a two-week period of the summer of 1950, J. C. Gill mapped the geology of the Mystery Lake area for the Manitoba Department of Mines and Natural Resources. This survey was concerned only with the geology around Mystery Lake and the immediate vicinity. The result of this survey, published as the "Geology of the Mystery Lake Area" (1951), was accompanied by a map at a scale of two inches to one mile.

In 1947 the International Nickel Company of Canada began a program of intensive geological and geophysical work in the area along the north side of the Hudson Bay Railway. The discovery of base metal occurrences stimulated interest in the area and much ground was staked. Subsequently, the Canadian Nickel Company, the International Nickel Company of Canada's exploration subsidiary, discovered a large low-grade nickel deposit at Moak Lake and a high-grade deposit at

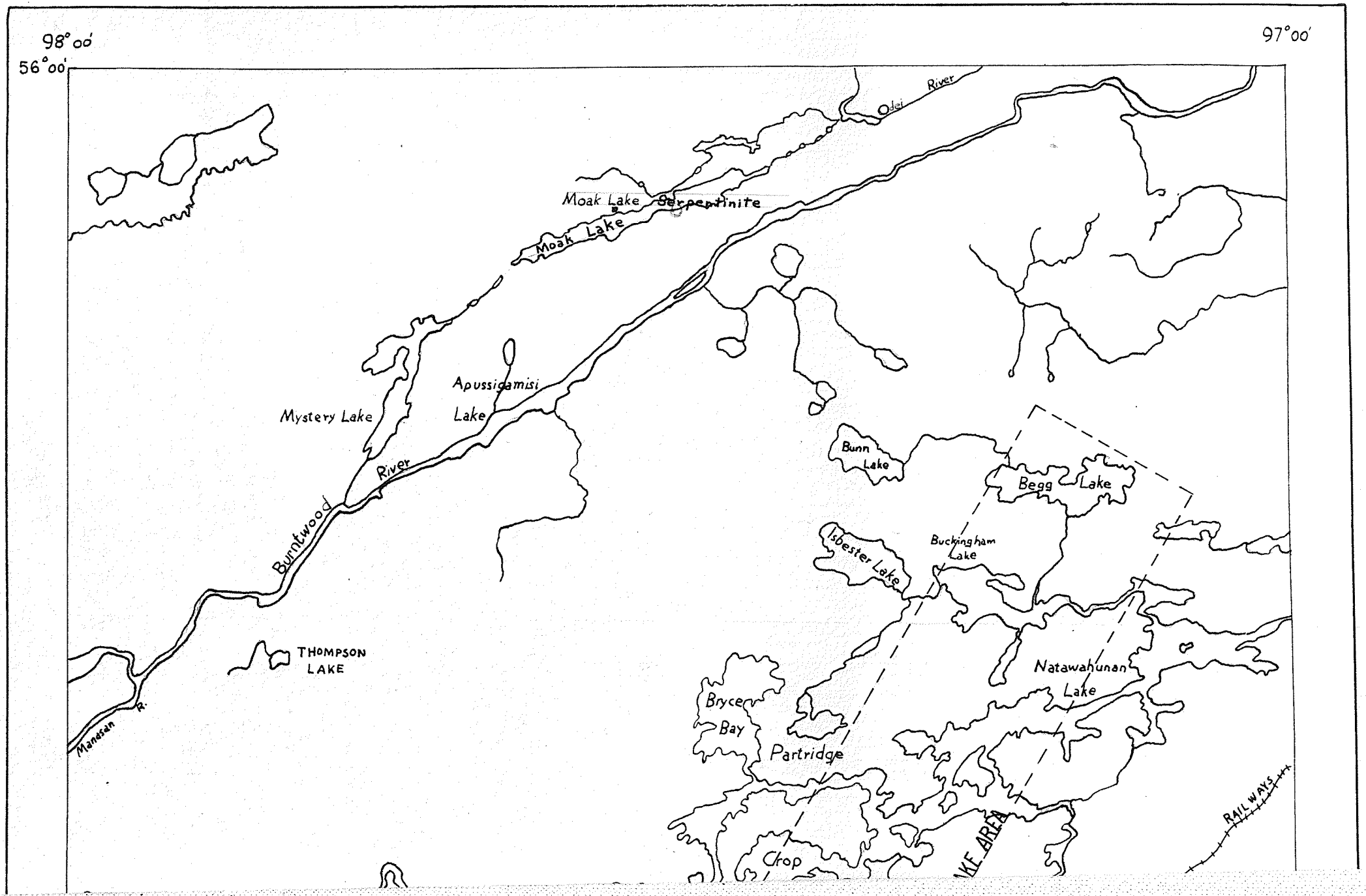
Thompson. The latter is to be brought into production by 1960. Further exploration by numerous mining concerns is still being conducted in the area.

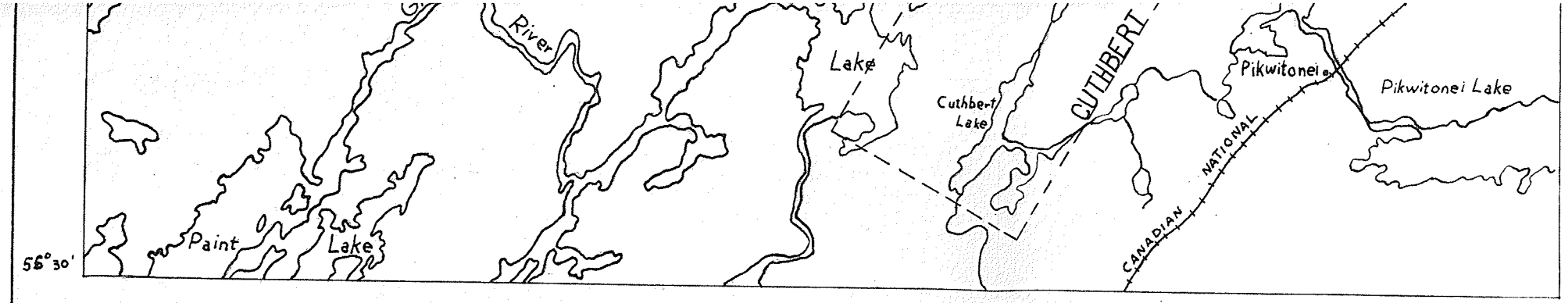
PRESENT WORK

The discovery of the large nickel deposits at Moak Lake and Thompson Lake drew much attention to this area of Manitoba. As a result of this interest, the Manitoba Department of Mines and Natural Resources initiated the mapping of the Thompson Lake - Moak Lake area on a larger scale than had heretofore been attempted. A five-man party under the leadership of J. M. Patterson was sent to the area in the spring of 1958 to begin the program. The writer was assigned to the party as senior assistant. During the summer of 1958, a portion of the area was mapped (see figure 1). The remainder is to be finished during the summers of 1959 and 1960.

It was suggested to the writer that the mapping of a peridotite dyke extending from Cuthbert Lake to Begg Lake and a comparison of this peridotite with the ultrabasic rocks of Moak Lake be made the basis of a thesis study. In accordance with this, the geology of Moak Lake was mapped, and a month was spent by the personnel of the field party studying the peridotite dyke and the surrounding area from Cuthbert Lake to Begg Lake. The winter months were spent

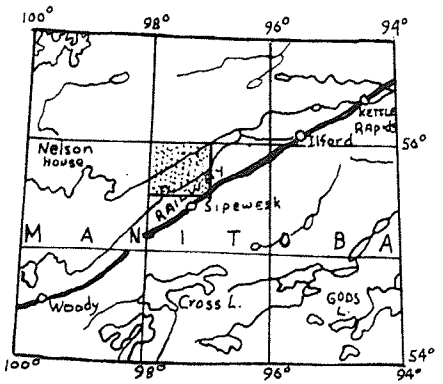
FIGURE I.


98° 00'
97° 00'
56° 00'
Odei River
Moak Lake
Serpentinite
Moak Lake
Apussigamisi Lake
Mystery Lake
River
Buntwood
Bunn Lake
Begg Lake
Isbester Lake
Buckingham Lake
THOMPSON LAKE
Manasan R.
Natawahunan Lake
Bryce Bay
Partridge
Crop
IKE AREA
RAILWAYS



THOMPSON LAKE - MOAK LAKE AREA

SCALE : ONE INCH = FOUR MILES



plotting the field data and studying rock specimens taken from the map-area.

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Thanks are due to the officers of the Canadian Nickel Company for supplying three sections of drill core across

the serpentinite body in which the ore is located at Moak Lake. Aid received from the personnel of the Assay Laboratory, Manitoba Department of Mines and Natural Resources, is also acknowledged.

CHAPTER II

DISCUSSION OF ULTRABASIC ROCKS

INTRODUCTION

In order to study the ultrabasic rocks of the area in their proper perspective, the writer has made a partial study of the literature pertaining to the characteristics and genesis of ultrabasic rocks in general. The following chapter is a summary of this study.

GENERAL CHARACTER

Throughout this report, ultrabasic rocks will be distinguished from other rock types on the basis of their silica content. This is in accordance with the definition adopted by Turner and Verhoogen (1951), as well as by Williams, Turner, and Gilbert (1955), in which ultrabasic rocks are those igneous rocks which have a silica content of 45 per cent or less.

The minerals composing the rocks of the ultrabasic suite are among the first ones to crystallize from a cooling magma. The major constituents are olivine, orthopyroxene, and clinopyroxene. Locally, spinel, iron oxides, and

sulphides are prominent. Minor constituents are calcic plagioclase, phlogopite, garnet, amphibole, and others.

The rock types within the ultrabasic group are normally characterized by the scarcity or absence of feldspar. One possible exception is anorthosite composed of anorthite with minor pyroxene, in which the low silica percentage requires that it be classified as an ultrabasic rock. The ultrabasic rocks are generally dark, due to the presence of a large amount of pyroxene. Partial or complete serpentinization of either olivine or pyroxene accentuates the dark appearance of these rocks. The rocks are generally medium- to coarse-grained, although the alteration to serpentine gives the surface a fine-grained appearance. Effusive rocks are rare. In fact, many doubt that a liquid magma corresponding in chemical composition to a rock of the ultrabasic group has ever existed.

A complete classification of the ultrabasic group of rocks was presented by Johannsen (1938). The two main groups are designated as peridotites and olivinites. Peridotite is composed primarily of orthopyroxene, clinopyroxene, olivine, and minor accessories; pyroxene predominating over olivine. Olivinite is composed of the same minerals as peridotite, but differs in that olivine predominates over the total quantity of pyroxene in the rock. Subordinate types are included in each of these two main

groups, and are distinguished by the relative proportions of the main constituents as well as by the presence of predominating minerals. The subordinate rock types will not be discussed. Some monomineralic or anchimonomineralic rocks are also classed within the ultrabasic system. Examples are pyroxenites (+90% pyroxene), dunite (+90% olivine), and anorthosite (a variety classed as an ultrabasic rock when composed of +90% anorthite). For the purpose of simplification, all ultrabasic rocks will be referred to as peridotites throughout this report unless otherwise specified.

FORMS OF ULTRABASIC ROCKS

Ultrabasic intrusions occur in several different forms, briefly described in the following paragraphs. Only two are considered in detail. They are distinguished as the Alpine-type peridotite (Benson, 1926) and the Bushveld-type peridotite (Hess, 1955).

One form of ultrabasic intrusion was called by Benson (1926) the sill and batholithic phase. Peridotite in this form exists as one of a series of associated intrusions which range from peridotite to granite. Turneaure (1955, p.56), in describing the igneous activity of the Sierra Nevada province, wrote:

"The intrusive sequence proceeds from basic and ultra-

> basic types to granodiorite and quartz-monzonite, the prevailing rocks of the main batholith and satellitic bodies. The ultrabasic intrusions, which occur in the Jurassic formations, have been involved in the folding and have been metamorphosed by the more acid differentiates that postdate the deformation. Intrusive bodies of peridotite also occur in the Franciscan formation which is later than the batholith."

The Caledonian group of intrusive rocks studied by Nockolds and Mitchell (1946) might also be classed with the sill and batholithic phase. These rocks are represented by intrusions, ranging from peridotite to granodiorite as well as aplite and some pegmatite, which all show a definite petrographic relationship.

This association of intrusions is found in orogenic provinces. It is noted that the intrusions range in size from sills to batholiths. The peridotites in these regions are perhaps a modification of the Bushveld type which will be discussed later. However, it is thought preferable by the writer to group this occurrence with those of the sill and batholithic phase.

Rocks of ultrabasic composition also occur as olivine bombs in basic lavas. These bombs are inclusions of olivine-rich rock, normally no greater than 2 feet in diameter. They are commonly elongated and in many instances possess a smooth surface, which is indicative of resorption to some extent. Olivine bombs have been reported from two main geographic zones. One zone extends from Breslau in west Poland to Saxony in central Germany. Another zone extends

west from Graz along the north flank of the Alps to the Black Forest. Occurrences are also reported from Hungary, Bulgaria, Sweden, France, Portugal, Sardinia, Japan, Morocco, Manchuria, Nigeria, and the Hawaiian Islands.

Another form in which ultrabasic rocks occur in relatively small quantities is that of stock-like intrusions. An intrusion described by Daly (1933) as a chonolith has been reported from Tulameen, British Columbia. The hortonolite pipes which cut the Bushveld complex and kimberlite pipes of South Africa may also be classed here.

LOCATION AND ENVIRONMENT OF THE ALPINE - TYPE PERIDOTITES

The Alpine-type peridotites are found associated with present-day island arc systems, major mountain systems, and the eroded roots of older mountain chains. Hess (1938-A) wrote that Alpine-type peridotites are strictly limited to such zones and are completely absent elsewhere.

These peridotites, with spilitic-type lavas, comprise the ophiolite suite. The members of this suite are not always closely associated. The peridotites are most often found in the areas where thrust faulting is most obvious on the surface. Hess pointed out that these rock types have been intruded only during the first period of deformation. Subsequent deformations do not have peridotite associated

with them. Spilitic lavas, however, occur throughout different tectonic parts of mountain ranges. They are not restricted to the first period of deformation, either, but occur during subsequent periods of tectonic activity.

Often associated with the Alpine-type peridotites are radiolarites and cherts as well as fine-grained pelitic limestones and greywackes. Benson (1918) pointed out that the peridotites are generally found in unaltered sediments, which may have a high water content. The sedimentary rocks indicate deposition during an unstable tectonic period, the presence of greywackes indicating that rapid erosion was occasionally prevalent. Turner and Verhoogen (1951) reported that spilitic lavas, also, are frequently developed as submarine extrusives. These associations indicate that Alpine-type peridotites were intruded into a submarine basin or into a structure which once existed as such.

The Alpine-type peridotites in many places are altered completely to serpentine; hence the name serpentinite, which is commonly applied to this type of rock. However, fresh dunite and harzburgite may be present in varying, although commonly minor, proportions within the serpentinized mass. Lenses of gabbroic rocks and pyroxenite are sometimes found associated with these peridotites in negligible amounts. Where these masses of serpentinite occur without associated unaltered ultrabasic rocks, the mesh and bastite structures of the serpentine indicate that it has been derived from an

olivine- or enstatite-rich peridotite.

The form generally taken by Alpine-type peridotites is that of long, narrow, steeply-inclined, sill-like masses concordant with the attitudes of the surrounding rock and parallel to the general strike of the structural lines in the surrounding region. Taliaferro (1943), in describing the serpentinite masses invading the Franciscan sediments of California, commented on the intrusive nature of these masses. Bodies of peridotite are concordant with the sediment, but small apophyses from the peridotite are found cutting the sediments. In addition, the occurrence of a large lens of peridotite on one limb of a fold is commonly represented on the other limb of the same fold by a series of smaller lenses of peridotite. According to Taliaferro, both of these phenomena indicate that the peridotite was intruded into the sediments.

The size of the Alpine-type peridotite masses varies considerably. Benson (1926) reported that the peridotite belt of Australia extends intermittently along a well-marked structural plane for a distance of 250 miles. The peridotite, although in many places only a few yards wide, may increase to a mile in width. Daly (1933) noted that the belt of peridotite in New Caledonia occurs in 22 separate bodies with a total outcrop area of 5500 square miles. The belt occupies a zone along the main axis of the island. Turner and Verhoogen described occurrences in southern New Zealand

as vertical sheets of Alpine-type peridotite, believed to be of late Palaeozoic age, dissected to a relief of 5000 to 7000 feet. They exceed 40 miles in length, and locally attain a width of from 3 to 5 miles. These ultrabasic masses are, however, usually much smaller, occurring as narrow lenses ranging from a hundred yards to a mile in length. These lenses often compose large parts of areas in which hundreds of similar sub parallel masses are arranged "en echelon" or in linear series along the axes of broadly contemporary fold mountain chains. Turner and Verhoogen (1951) stated that in North Carolina several hundred individual masses, rarely exceeding 100 yards in width, have been mapped along the axis of the former Appalachian mountain chain.

According to Benson (1926), Suess believed that the intrusion of the Alpine-type peridotites took place during a period of orogeny, and occurred along bedding planes between which there had been differential movement. From a study of comparatively recent belts of ultrabasic rocks in the East Indies and West Indies, Hess (1938-B) concluded that the peridotite was always present in the most deformed zones and that it had been intruded during the first period of deformation. A second period of deformation within the area resulted in no further intrusion of ultrabasic rock.

Hess (1937) has compiled a comprehensive list of occurrences of Alpine-type peridotites throughout the world. The following summary from Hess's list indicates the spatial distribution of the occurrences. Hess believed the ages of these occurrences to range from Precambrian to Tertiary. He divided the occurrences between present island arcs and mountain systems and their eroded roots.

A. Present Island Arcs
   1. West Indies
   2. East Indies
   3. New Guinea

B. Mountain Systems and their Eroded Roots
   1. Andaman Islands, Burma, and along the Himalayas to Arabia
   2. Northern Caucasus
   3. Ural Mountains
   4. Alpine belt of southern Europe
   5. Pyrenees to the Dinardes, continuing to southern Asia Minor
   6. The east-west belt in central France
   7. The belt along the Finland-Russia border
   8. Newfoundland to Alabama
   9. Alaska to Lower California
   10. Northern South America to Ecuador
   11. In Africa from the Sudan to the southern tip of

the continent

From the above compilation, it is evident that the Alpine-type peridotites, though of world-wide distribution, are restricted to regions intensely disturbed by over-thrusting and alpine orogeny.

LOCATION AND ENVIRONMENT OF THE BUSHVELD - TYPE PERIDOTITES

The Bushveld-type peridotites occur in an entirely different tectonic setting from the Alpine-type. The most common occurrence is as a basal phase in layered lopoliths or basic sheets and sills. There, the peridotite occupies the lower portions of the structure. From this basal phase, the rock grades upwards into norites, gabbros, and other less basic rocks. The change from one rock type to another may be gradational or a sharp boundary may exist between them. These peridotites are found in regions which have not undergone contemporaneous orogeny. In a few places, however, they are associated with volcanic provinces, and seem to be chemically equivalent to strictly volcanic series dominated by basaltic lavas.

The most common occurrence of this type of peridotite is as a basal member of lopoliths. Lopoliths are funnel-shaped intrusions which have an unconformable contact with the enclosing rock. They have a roughly elliptical plan

view. The igneous rocks within the structure often exhibit banding, the individual bands of rock dipping in toward the centre. The dip decreases from the edge inwards and is shallower than that at the contact between the structure and the intruded rocks. The resulting layers of a lopolith resemble saucers stacked one upon the other, lying concave side upwards.

Peridotites form the basal phase in a number of known lopolithic structures. The Bushveld lopolith, after which the type is named, occurs in the Transvaal, South Africa. It is an immense intrusion, covering an area of approximately 20,000 square miles, and having a vertical section of as much as 5 miles. Only ultrabasic rocks occur in the trough of the intrusion. Their thickness was first estimated at 15,000 feet, but subsequent drilling has indicated that they are much thicker than this (H.D.B. Wilson, 1956). The ultrabasic rocks grade upward into norites and gabbros and possibly into granitic-type rocks. Several other structures generally accepted as being the same type are: the Sudbury lopolith of Ontario, the Kungwe Bay lopolith of Tanganyika, the Insizwa intrusion, the Stillwater complex of Montana, the Duluth gabbro, the Baltimore gabbro, and those intrusions of a similar type which occur along the Ural Mountain system. These intrusions, whether large basic sheets or lopoliths, are all characterized, like the Bushveld, by a layer of ultrabasic rocks along the base and by an upward gradation

into basic and intermediate rocks.

A second type of structure, with a cross-section similar to a lopolith, differs from it by having the surface expression of a dyke. The Great Dyke of Southern Rhodesia is the only reported example of this type. It is approximately 300 miles long and from 3 to 7 miles wide. Because the ultrabasic rocks which form the basal part of it grade upward into basic rocks, the structure is thought to have the same origin as the lopoliths despite its different surface expression.

Intrusive rocks occurring as a still different structural type, but showing a gradation from ultrabasic to gabbroic and dioritic rocks are also known. Instead of having been intruded as a liquid magma with differentiation proceeding "in situ", this type is believed to have differentiated in a subterranean magma reservoir with subsequent intrusion producing rocks of different compositions. Wager (1958) stated that a remapping of such rock types on Skye is building up wider evidence to indicate that they were a bottom accumulation of a layered peridotite complex. Subsequent injection produced the dykes and sills of different compositions represented by the ultrabasic and basic assemblage. This type is thus but a variation of the Bushveld-type peridotite, the processes of differentiation and intrusion being reversed.

DISTINCTIONS BETWEEN ALPINE-TYPE PERIDOTITE AND BUSHVELD-TYPE PERIDOTITE

A review of a portion of the available literature on Alpine and Bushveld peridotites indicates numerous criteria by which the two types may be distinguished. Some of the following points have been adopted from Hess (1958).

1. Alpine-type peridotites are usually intruded into sediments and lavas associated with mountain structures. They bear no direct relation to other igneous rocks in the area. On the other hand, the Bushveld-type peridotites generally show a systematic connection to other basic igneous rocks in the vicinity.

2. Primary banding is rare in the Alpine type and common in the Bushveld type.

3. Alpine-type peridotites are associated with areas showing evidence of over-thrusting and orogenic deformation; Bushveld-type peridotites occur in areas which have no evidence of a period of contemporaneous orogeny.

4. In general, the ultrabasic rocks of the Alpine type are intensely serpentinized; whereas those of the Bushveld type, in continental masses, are anhydrous except for local alterations.

5. The orthopyroxenes of the Alpine-type peridotite are commonly stout prisms. However, nearly euhedral, settled crystals of olivine, included in a matrix of poikilitic

orthopyroxene, characterize the Bushveld type.

6. The ratio of ultramafic rocks to feldspar-bearing rocks is approximately 1:10 in Bushveld types. Feldspathic rocks are absent or present in only minute amounts in associated Alpine-type rocks.

7. Although the Mg/Fe ratio for Alpine-type peridotite is usually above 7.5, that of the Bushveld type generally ranges between 3.5 and 7.5.

8. Alpine-type peridotites have a lower content of CaO and Al_2O_3 than Bushveld-type peridotites.

9. Orthopyroxenes from the Bushveld type commonly contain 1.3 to 1.9 per cent CaO, which, on slow cooling, exsolves as fine diopsidic lamellae parallel to [100]. Alpine-type peridotites generally contain less than 1.3 per cent CaO and hence fewer diopsidic lamellae form in the grains.

10. Accessory chromite is present in nearly every thin section of the Alpine-type. It is less abundant or absent in the Bushveld-type, due to its concentration in layers.

11. Evidences of high-temperature contact metamorphism are conspicuous in the rocks associated with the Bushveld-type peridotites. However, the rocks enclosing the Alpine-type peridotites show very slight evidence of metamorphism, even around the largest bodies.

12. The Alpine-type peridotites generally show strong

optical orientation of the constituent olivine. Translation parallel to [100] is not uncommon. In masses altered to serpentine, the resulting antigorite flakes also show a preferred orientation. This is not as obvious in Bushveld-type peridotites. In the lopolith structure, it is practically absent.

13. Chill phases of lopoliths in which Bushveld-type peridotites occur are of gabbroic composition. Alpine-type peridotites have no chill phase.

No single criterion can serve as an absolute indication that a given peridotite belongs to one of the two groups. However, by using a combination of the criteria, a peridotite belonging to either of the groups can be classified with reasonable certainty.

DIFFERENCES IN THE ORIGINS OF ALPINE-TYPE PERIDOTITES AND BUSHVELD-TYPE PERIDOTITES

The origins of these two rock types have been discussed frequently throughout the literature. It has been generally concluded that the differences exhibited by the two types of peridotites directly reflect the differences in the origins. The following is a summary of some of the ideas and problems connected with the origins of these two similar rock types.

THE BUSHVELD-TYPE PERIDOTITES

The association of Bushveld-type peridotites with basic rocks and the great preponderance of basic rocks over ultrabasic rocks has led to the conclusion that the parental magma was basaltic in composition. A feature substantiating this conclusion is the occurrence of basaltic selvages wherever chilled zones are found in conjunction with these peridotites.

In 1928, Bowen published results on the phase relations of important constituents of basaltic magmas and supported these results with field observations. Careful study by petrologists of various igneous structures has accumulated a wealth of evidence showing that the process of crystal differentiation as outlined by Bowen does apply in the field.

A very brief description of the process of crystal differentiation is as follows. During the slow cooling of a basaltic magma, the first mineral to form is olivine. The composition and quantity of the olivine are determined primarily by the composition of the original magma and the rate at which it is cooled. The formation of olivine at an early stage in the cooling history of a basaltic magma has long been noted in the field and has also been proven by laboratory experiments. The olivine, being denser than the parental magma, sinks in it, accumulates on the floor of the intrusion, and is effectively removed from further

reaction with the magma. Similarly, the next minerals to form, in most cases orthopyroxenes, also sink in the liquid, as they too are denser than the magma. As this process continues, the magma is gradually depleted in the constituents which form the first crystals. These constituents are primarily iron and magnesium. At the time orthopyroxenes begin to form, calcium-rich plagioclase starts crystallizing. Finally, the composition of the magma becomes such that on further cooling, the formation of olivine and orthopyroxene gives way to the formation of less basic monoclinic pyroxenes and amphiboles with calcium and aluminum becoming dominant in their composition. As the magma becomes less basic, the crystallization of the plagioclase continues until the magma has become solid; the calcic plagioclase becoming more sodic as crystallization proceeds, according to the principle of continuous reaction. In the final stages, the residual constituents solidify, with the common formation of aplite and pegmatite dykes.

A study of this process indicates that the first layers to form in an intrusion would be rocks rich in olivine and orthopyroxene, a typical peridotite. Proceeding upward in the section, norite would be found: a mixture of basic plagioclase and orthopyroxene. Higher still, gabbro would be encountered. This would mark the stage at which the crystallization of clinopyroxene began to dominate over that of orthopyroxene in the solidifying magma. The succeeding

rocks would gradually become less basic up to the final products of consolidation.

Field examples used to exemplify the Bushveld-type peridotite provide evidence in support of this process. The basal members consist of ultrabasic rocks and there is an overall gradation through norites to gabbros and even into granophyres in some cases. This continuous gradation is broken when a detailed study is made; repetitions of bands occur, and gradations are sharp in places. Nevertheless, the underlying principle still applies.

Coupled with this overall gradation in rock type is evidence of crystal settling. Structural relationships such as cross bedding, graded bedding, landslides of crystals, and ripple marks are found in these igneous rocks. These are similar to the structural relationships found in grains which have settled under aqueous sedimentary conditions. This is certainly strong evidence for the accumulation of crystals from a liquid magma. In addition, the detailed petrologic and petrographic examination and the study of the distribution of major elements and trace elements of the Skaergaard intrusion by Wager and Deer (71) have confirmed the basic principles of crystal differentiation as outlined by Bowen. Also, numerous other examples could be quoted which support this widely accepted theory.

THE ALPINE-TYPE PERIDOTITES

The process of crystal differentiation described by Bowen (1928) adequately solves the problem of the origin of the Bushveld-type peridotite. However, the origin of the Alpine-type peridotite is still highly controversial. A summary of the various aspects of this problem is presented in the following paragraphs.

Development of Theories Concerning Origin and Emplacement

In 1930, Bowen and Schairer worked out the phase relationships for the system MgO - FeO - SiO_2. The results obtained by this work were applicable to the Alpine-type peridotite problem since the system studied embodied the primary constituents of this rock type. Previous to this, a theory accepted by many petrologists and championed by Vogt was that this peridotite evolved from the injection of a peridotitic liquid which was formed by the remelting of accumulations of olivine crystals.

The average composition of the olivine in Alpine-type peridotite is approximately Fo 90. Vogt assumed that the addition of 20 per cent of the fayalite molecule to forsterite would lower the melting point of the olivine from 1890°C to 1500°C. Even this temperature of intrusion was very high, in the light of that which was estimated from

examinations of the state of metamorphism of the enclosing rocks. Bowen and Shairer's work showed, however, that olivine must have 75 per cent of the fayalite molecule to be completely liquid at 1500°C. and must have at least 40 per cent to even begin melting at this temperature. Study of the olivine system shows that the temperature at which the most common olivine in these peridotites begins to melt is approximately 1850°C. Because of the close approximation of this system to the naturally occurring rocks and the high temperatures that would be required for the injection of a peridotitic liquid corresponding to this composition, Vogt's theory was abandoned by most petrologists.

In 1938, Hess introduced a new theory accounting for the formation of the Alpine-type peridotites. Because of the partial or complete serpentinization of these Alpine-type peridotite bodies, he postulated the existence, at depth, of a hydrous magnesium-rich magma containing between 5 and 15 per cent water. Hess visualized the magma as approximating the composition of serpentine. This magma was proposed to represent the lowest melting portion of the peridotitic layer which, as postulated from seismic evidence, constitutes the upper layer of the earth's mantle. Hess believed that the presence of a high water content in the magma would lower the temperature enough to make the existence of a peridotitic-type magma credible. Also, he believed it would account for

the serpentinization of many of these peridotites.

In order to study the possibility of the existence of a serpentine magma at depth, such as the one proposed by Hess, Bowen and Tuttle (1949) made a study of the phase relations for the system MgO - SiO_2 - H_2O, a system closely approximating the composition of the proposed magma. Temperature and pressure conditions in this study carried up to 1100°C. and 40,000 p.s.i. However, it was found that pressure had a negligible effect on the temperature at which the reactions took place.

From this study, Bowen and Tuttle were able to show that forsterite is stable in the presence of water vapor at all temperatures above 400°C. Below this temperature, forsterite alters to serpentine and brucite. If silica is added to this system, serpentine can form up to 500°C. This temperature is the upper limit for the formation of serpentine. Above 500°C., with sufficient water vapor present, forsterite alters to talc; with insufficient water vapor, to enstatite and talc. Thus the results of this study precluded the possibility of the intrusion at low temperatures of a magma of serpentine composition which would crystallize, wholly or in part, directly into serpentine. The results also showed that if magmas approaching serpentine in composition do exist, they are completely crystalline as olivine and pyroxene at 900°C. and the water is present as a vapor.

From a study of peridotite dykes on the Isle of Skye, Bowen (1928) postulated a method for the intrusion of dunite. This theory has been accepted by many geologists and Bowen has applied it, with a few modifications, to the formation of Alpine-type peridotite (Bowen and Tuttle, 1949). The theory postulates the presence of a layer of olivine crystals with only traces of water vapor present. This can be a layer either within the mantle of the earth or formed by the accumulation of olivine from a basaltic magma. Under certain conditions of crustal tectonics, this crystalline mass can be forced into accessible portions of the earth's crust. The movement of the mass is lubricated by a thin film of water, "sometimes only two molecular diameters thick" (Sosman, 1938). Any serpentine forming below 500°C. would facilitate the movement of the mass. Bowen also accepted the idea proposed by Hess that the crystalline mass may incorporate water from the enclosing rock which would aid in the development of serpentine and thus in the ease with which it is emplaced.

This theory is supported to a certain degree by field evidence. The absence or very limited size of a zone of contact or thermal metamorphism around occurrences of Alpine-type peridotite has been reported from all over the world (Ross et al, 1954). Sosman (1938) has described an inclusion of partially altered coal within a peridotite dyke in North

Carolina. After extensive testing based on the content of three constituents of unaltered and altered coal, he arrived at the conclusion that the temperature of intrusion of the dyke was between 480 C. and 550 C. Dunites form the island of St. Paul's Rock and have been described by Tilley (1947). These rocks, which form part of the Mid-Atlantic ridge, are commonly supposed to have a deep-seated origin. The olivine and enstatite exhibit excellent fluxion structure. Translation gliding of the olivines and minutely ground fragments of both minerals are interpreted as resulting from dynamic movement of the rock, likely at the time of emplacement. Turner (Ross et al, 1954) studied the structure of the dunites of New Zealand and compared them to those on the Isle of Skye. He concluded that those of New Zealand must have formed by the laminar flow of a partially, perhaps almost completely, crystalline mass. Thus it is evident that Bowen's theory of the origin of emplacement of Alpine-type peridotites is supported by abundant field evidence as well as by evidence based on laboratory experiments.

In spite of this, Hess (1955) has recorded abundant field evidence which disagrees in part with Bowen's theory. Bowen called upon orogenic disturbances to provide the force for the intrusion of a crystalline aggregate of dunite. He claimed that as the dunite mass became partially serpentinized, flowage would be greatly facilitated. However, Benson (1918) indicated that most of the serpentine was of normal mesh

structure and not schistose. Hess (1955) pointed to this fact and commented that the delicate mesh-like structure of the serpentine would probably be destroyed on flowage. This was taken as evidence to indicate that if the mass had flowed, flowage must have preceded serpentinization. One of the prime problems of Bowen's theory was, however, that of the serpentinization of the dunite or peridotite mass.

The Serpentine Problem

The fact that serpentine is present in various quantities within Alpine-type peridotites has been a perplexing problem to most workers. Benson (1918), in a survey of the literature on the origin of serpentine, presented proof that serpentinization is an autometamorphic process. This has been amply supported by the investigations of later workers on the subject. It has long been recognized, also, that any thermal metamorphic and hydrothermal metamorphic effects associated with serpentine bodies are not extensive. C. S. Ross (Bowen and Schairer, 1933) stated that dunite areas of North Carolina have contact zones approximately 4 centimeters wide in enclosing quartz-rich shists where hydrous minerals have formed. Benson (1918) reported slight hydrothermal metamorphic effects accompanying the intrusion of peridotite in some occurrences. These take the form of a few antigorite veins extending from the peridotite into the country rock. Examples have been

reported in which there is evidence for the expulsion of soda from peridotite. This is revealed by the development of albititic veins in the enclosing rock and the development of glaucophane shists around some ultrabasic bodies (Taliaferro, 1943). An analysis of the country rock proceeding away from one peridotite contact showed a decrease in soda from 8.12 per cent to 2.9 per cent within 6 feet (Benson, 1918). Benson mentioned that there is evidence that H_2CO_3, SiO_2, HCl, Na_2O, boracic acid, and some H_2S have accompanied the intrusion of peridotite in some cases. Taliaferro (1943) claimed that calcite, albite, and quartz veins, cutting ultrabasic rocks and the enclosing rock, have been derived from magmatic aqueous solutions accompanying the intrusion. Effects such as these are rare, however, and are never extensively developed; this indicates a general lack of water present in the intrusion. These facts, plus the fact that the development of serpentine is entirely unrelated to weathering phenomena, has led to the general conclusion that serpentinization is an autometamorphic process, as indicated by Benson, and that the intruded mass was not excessively water-rich. As Alpine-type peridotites have a world-wide distribution, the problem of serpentinization has a great bearing on their genesis.

Bowen and Tuttle (1949) pointed out that when olivine becomes serpentinized, brucite is also formed. This has been realized from equations representing the reaction.

The formation of serpentine from olivine with the introduction of the required reactants results in a large volume increase. However, very few authors have reported finding evidence of a volume increase accompanying the alteration and many have found no evidence for an increase at all. Furthermore, brucite is very rarely found within these altered rocks.

Equations representing the serpentinization process are given by Turner and Verhoogen (1951) and presented below. The volume increase is evident in both equations.

$$3Mg_2SiO_4 + 4H_2O + SiO_2 \longrightarrow 2H_4Mg_3Si_2O_9$$

(forsterite) (420 gms.; 131 c.c.) (introduced) (serpentine) (552 gms.; 220 c.c.)

$$2Mg_2SiO_4 + 2H_2O + CO_2 \longrightarrow H_4Mg_3Si_2O_9 + MgCO_3$$

(forsterite) (280 gms.; 88 c.c.) (introduced) (serpentine) (276 gms.; 120 c.c.) (magnesite) (84 gms.; 28 c.c.)

If the excess material is removed in solution as required by the second equation, a closer approximation to original volume remains. However, an appreciable volume difference still exists. This is complicated by the fact that enormous quantities of water are required to remove the excess magnesium from the serpentine. Evidence for the existence at one time of large quantities of water is lacking and no increase in magnesium is found in the enclosing rocks.

The peridotite magma hypothesis of Hess (1938) avoided this problem. He showed that if the water and the required silica for serpentinization are present in the original accumulation of olivine crystals, no volume increase will take place on the alteration of this mass to serpentine, as shown in the following equation (Turner and Verhoogen, 1951).

$$\underset{\substack{\text{(forsterite)}\\ \text{(121 c.c.)}}}{2Mg_2SiO_4} + \underset{(\pm 61\ \text{c.c.})}{H_4SiO_4} + \underset{(\pm 36\ \text{c.c.})}{2H_2O} \longrightarrow \underset{(220\ \text{c.c.})}{2H_4Mg_3Si_2O_9}$$

This hypothesis has been questioned by Bowen and Tuttle's work (1941) for the pressure and temperature conditions which are assumed to exist at the top of the peridotite layer. The equation is, however, the only one which fits the observed facts.

Origin of Alpine-type Peridotites

The development of existing mountain ranges from sediments connected with geosynclines has long been recognized by geologists. The fact that Alpine-type peridotites are associated exclusively with regions subjected to mountain-building compressional forces has also been realized. Because of these facts, it is believed that Alpine-type peridotites might have originated at depth. The source called upon by many geologists has been the peridotite or dunite

layer which is commonly thought to form the top layer of the earth's mantle. Part of the process of mountain building takes place at depth and it is during this phase of the process that the emplacement of the peridotite is believed to take place. As has been previously mentioned, Alpine-type peridotites are found without associated less basic rocks. This is a unique feature in their occurrence, as differentiation "in situ" cannot then explain their origin. A study of the roots of exposed mountain systems shows that the rocks have been subjected to intense regional metamorphism. This is indicative of burial at depth within the crust, possibly near or below the normal depth of the mantle, the source of the ultrabasic material.

An interesting fact concerning the origin of Alpine-type peridotites has been discussed by Ross et al (1951, 1954). The authors have compared the minerals found in these peridotites with those which compose olivine-rich inclusions or olivine bombs found in basaltic rocks. The olivine bombs, as previously mentioned, are found mainly in two geographic belts, although they are also present in various areas throughout the world. Both rock types are composed primarily of olivine and enstatite with minor diopside and spinel. Studies of the composition and trace elements present in the minerals from Alpine-type peridotites and olivine bombs produce striking similarities. In the olivines studied,

there is a variation of only 1 per cent silica and 2 per cent magnesia. The similarity is not as pronounced for the other minerals. However, the similarity of the olivines in these rock types does suggest a common source for the rocks. The most logical common source is the peridotite layer forming the top part of the mantle.

The presence of a peridotite layer existing below the Mohorovicic discontinuity is not known with certainty. However, seismologists have long proposed its existence (Gutenberg, 1951), as it is the only known rock type which transmits seismic waves at the observed velocity for this region of the earth under the postulated temperature and pressure conditions. Geological contrasts between the continents and ocean basins show that as the mantle is approached, rocks become more basic. Coupled with the other geological observations mentioned, the existence of a peridotitic layer forming the upper part of the mantle is a credible hypothesis. Such a layer is the most logical source for the origin of the Alpine-type peridotites.

The Nature of Island Arcs and their Relation to Alpine-type Peridotites

Island arc systems have long been recognized, and have been the subject of considerable speculation. The discovery by Vening Meinesz (De Sitter, 1956) of large negative

isostatic gravity anomalies associated with them has led in recent years to much study of their structure and to theories regarding their importance in orogenic processes.

Island arcs are groups of small islands, commonly volcanic, which form an arcuate surface expression, concave side towards the mainland. Exceptions to this are few. These exceptions are similar to island arc structures in every detail except that they have a linear instead of an arcuate surface expression. Island arc structures are common along the north and west borders of the Pacific Ocean. They extend almost continuously from the Aleutian Island chain off the coast of Alaska, southwest through Japan, the Philippines, and on to New Guinea. The West Indies island arc is the only one developed in the Atlantic Ocean which is still active.

A review of the literature reveals several features common to most arc systems. The following points have been taken from papers published by geophysicists of the Lamont Geological Laboratory, H. H. Hess, and other authors.

1. Island arc systems of the Pacific Ocean follow the trace of "the Andesite line" which separates andesite volcanism of the continents from predominantly basaltic volcanism of the ocean basins. The same is true of the West Indies island arc system. The arcs thus mark a major petrological boundary.

2. Where island arc structures exist, they separate the stable oceanic areas from the stable continental areas.

3. The arcs are always concave towards the continental regions wherever an arcuate form is present.

4. Deep trenches are found on the concave side of arcs and remain parallel to them throughout the length of the arc system. The deepest parts of the Pacific Ocean are found at the bottom of the trenches.

5. The slope of the walls of existing trenches is from 3 degrees to 15 degrees.

6. Large negative isostatic gravity anomalies are associated with the outer convex side of the main arc. The anomalies appear to be a single continuous band for each arc system. They usually correspond to the position of the deep trench, but in some places they are independent of the trench and are found over the islands of the main arc.

7. Negative isostatic anomalies are rarely over -200 milligals, and -150 milligals is common. These exceed all continental anomalies.

8. The width of the negative strip averages 150 kilometers, with the strongly negative part usually less than 50 kilometers wide.

9. The negative anomaly is commonly bordered on either side by belts of positive anomalies which generally correspond to topographic swells. The inner swell is usually emergent and forms the islands of the arc system.

10. Where geological evidence is available on islands forming arc systems, extreme folding and overthrusting towards the trench is indicated. This zone of deformation is relatively narrow and is bordered by a broad zone of mild deformation.

11. The arc area is composed of upthrust rock which contains volcanic rocks, peridotites, radiolarian cherts, and greywackes.

12. Volcanoes associated with the East Indies and West Indies arc systems lie on the concave side of the arc approximately 100 kilometers to 150 kilometers away from the axis of the negative anomaly. These are predominantly andesitic types. Numerous volcanoes are also found on these and other arc systems associated with the islands forming the arc itself. These are aligned parallel to the negative anomaly along the topographic high for the island arc.

13. Peridotite intrusions occur along or close to the negative strip and within 75 miles of it. Commonly two belts are formed, one on either side of the negative anomaly and parallel to it.

14. Correlations of seismic activity with present day island arcs (Benioff, 1954) and with the west coast of South America show the presence of planes along which the earthquakes are aligned. Earthquake epicenters vary from shallow under the trench to deep-seated under the continental margins.

From a study of shock waves, these planes are believed to represent fault planes dipping under the continental sectors at angles varying between 30 degrees and 60 degrees, depending on the arc system and the depth of the position of the plane. Shock waves also indicate that the plane is a thrust fault with movement such that the continental area is moving relatively over the oceanic area. The fault plane is believed to extend between 175 kilometers and 720 kilometers into the mantle, the depth at which seismic activity ceases.

The following data deal only with the West Indies system and along the Tonga Trench, the only two areas for which seismic reflection work was found available.

16. The crust thickens from the oceanic sections to the base of the trench. This is from 12 kilometers below sea-level in the ocean to 20 kilometers below sea-level beneath the trench for the Tonga region. The crust varies from 4 kilometers thick in the oceanic region to 7 kilometers thick under the trench for the Puerto Rico area.

17. Few or no sediments are found in the trenches.

18. Seismic profiles across the Puerto Rico trench area show that the crust is raised under the island arcs and depressed under the trenches.

19. The Caribbean basin section on the concave side of the West Indies arc is intermediate in nature between oceanic sections and continental sections. No normal Mohorivicic discontinuity was found in this area.

20. The depths to the Mohorovicic discontinuity in the oceanic section are 5 kilometers below sea bottom. Below this break, seismic velocities indicate rocks of ultrabasic composition.

Several interpretations have been given for these facts. It is readily apparent from geological evidence, and supported by seismic evidence, that island arc areas are ones of intense compressional deformation. The trench areas are interpreted as being the surface trace of thrust fault planes dipping under the continental sectors (Benioff, 1954). These facts indicate that island arc systems mark major structural discontinuities as well as petrographic discontinuities between the continental and oceanic areas. Officer et al (1957) interpreted the Caribbean area on the concave side of the West Indies island arc as representing a portion of oceanic crust which is in the process of being converted to continental crust. This is in accord with the theory that island arc systems represent the first stage in the process of mountain building. Mountain-type structures found in these regions plus the obvious orogenic movements in the area and the general instability of the region as shown by the large isostatic gravity anomalies present, suggests this theory. The presence of Alpine-type peridotite associated with island arc systems is a further indication that the theory is correct. Although the association between island arcs and the formation of mountain ranges remains to be proven,

it is becoming more widely accepted by geologists and geophysicists throughout the world.

With the assumption that island arc systems do represent embryonic mountain ranges, the source for Alpine-type peridotites and their method of emplacement becomes, perhaps, more readily apparent. Peridotite rocks are present in island arc systems. Seismic evidence indicates that the depth to rocks of ultrabasic composition is approximately 5 kilometers below the ocean bottom. The deepest position of the ultrabasic layer in trench areas where seismic work is available is 20 kilometers below sea-level (Raitt et al, 1955). Birch (1955) calculated temperature gradients for various sections of the earth's crust. The postulated temperature existing at a depth of 20 kilometers in island arc areas does not exceed 500°C.

If the conclusions of Bowen and Tuttle's work (1949) are correct and if these proposed temperature gradients are correct, then at the top of the ultrabasic layer in these regions, conditions are such that serpentine could exist. It would be in the solid form and not in a hydrous magnesian-rich melt as proposed by Hess (1938). Also, if the ultrabasic layer were dunite or peridotite, and if compression in the area of the island arc system forced some of it into higher horizons, the temperature of the mass would not inhibit alteration to serpentine. Then, on coming in contact with water vapor, it would alter to serpentine in such

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quantities as there is water vapor available.

But this does not alleviate the problem that, during alteration, excess material must be removed as indicated in a previous section. As no evidence for the removal of material is present in Alpine-type peridotite bodies, alteration of dunite to serpentine cannot have taken place at the position where it is now exposed. Perhaps removal of excess material or an increase in volume took place at the mantle, or at a section lower than that at which the peridotite is now exposed. If so, evidence for this change would not be present in the rocks now enclosing these peridotites, and this hypothesis would be tenable. Hess (1954) postulated that minor differences in velocity observed from seismic work for the layer below the Mohorovicic discontinuity might be correlated with the degree of serpentinization of the peridotite at this horizon. If this is correct, it is the only evidence of alteration to serpentine at this depth.

Bowen indicated that water vapor would be rare at the depth which was postulated for the existence of the peridotite layer. But these observations might not be as valid at the temperature and depth at which the peridotite layer is now believed to exist. Perhaps water vapor does exist in such quantities at these conditions that a portion of the dunite could be serpentinized. Then compression in an island arc area would force a mass composed partly of dunite and partly

of serpentine to higher levels. The distribution of the two types with respect to each other would then be fortuitous, as is found in surface exposures.

This situation would explain many of the problems connected with the intrusion of Alpine-type peridotites. It would explain the low temperature of intrusion of dunite and its resulting granulation. The absence of associated basic rocks would be accounted for. Benson (1918) indicated that many bodies of dunite are peripherally serpentinized. This could be due to the intrusion of solid dunite which, on coming into contact with water vapor at higher surroundings, would alter to serpentine along its margins. As sediments were forced into the hotter portions of the crust, excess water in the form of water vapor would stream upwards along zones of weakness. As intruding peridotite masses would undoubtedly follow these same zones of weakness to the surface, the coincidence of water vapor with peridotite in these zones could conceivably account for a large part of this peripheral alteration. If peripheral serpentinization of dunite bodies did take place, then less force would be required for further intrusion because of the ease with which serpentine shears. Water being driven off from sediments, and incorporated into ultrabasic rocks, might account for many of the small lenses of serpentine that exist along the Appalachian chain. Also, if only the outside of a serpentine body was sheared during emplacement, the fine mesh structure

of serpentine so often observed would be more easily preserved in the interior portions. By postulating the existence of a layer on the top part of the mantle composed of both serpentine and dunite or peridotite, most, if not all, the problems associated with the intrusion of Alpine-type peridotite bodies can be explained.

But what of the method of intrusion of these bodies? Hess has suggested a plausible means. He believed that, under compressional forces which exist in island arc structures, a lens of dunite altered to serpentine at its border, or a lens of serpentine, would move through the enclosing rock along zones of weakness much as a melon seed does when squeezed between one's fingers. This would shear the borders of the ultramafic body and leave the interior more or less intact. Taliaferro (1943) described bodies of serpentinite which he believed were serpentinized at depth and intruded to their present position as a solid. Shearing along the margins of other serpentine bodies described by the same author has been attributed to the volume increase due to alteration of dunite to serpentine in place. This shearing could possibly be due to the emplacement process only.

The occurrence of olivine bombs in basaltic magma can be interpreted in the light of the new seismic evidence and temperature gradients. Consideration of the temperature at which basalt melts, the geothermal gradient and the composition of the crust and mantle indicates two possible origins for

basaltic liquid. Differential fusion of the peridotitic mantle rocks along the proposed major fault planes dipping under the continents could generate a basaltic magma. Powers (1955) has proposed a similar origin for the Hawaiian Islands basalts. A local increase of radioactive heat within the crust might cause differential fusion with the production of a basaltic magma. The Mohorovicic discontinuity is much deeper under continental areas than it is under oceanic areas. Thus, it is conceivable that a basaltic magma generated within the continental mass could be intruded into the mantle in an oceanic section. The intrusion of such a magma to the surface of an oceanic area would pass through the surface peridotite layer of the mantle and possibly incorporate some of this material. The heat of the basaltic magma would only convert any serpentine in the incorporated peridotite to olivine, as the temperature of the magma would not be great enough to melt the olivine. Olivine would remain in the basalt as a solid forming the bombs found in these intrusive layers. This agrees with the hypothesis of Ross et al (1954) which states that Alpine-type peridotite and olivine bombs have a common source.

CONCLUSIONS

By combining the results of laboratory work with field evidence, a satisfactory hypothesis for the origin of Bushveld-

type peridotite was found. These methods of study combined with seismic work have finally succeeded in forming a credible hypothesis for the origin of Alpine-type peridotites. Although details still have to be explained for both rock-types, many workers now agree that the main problems concerning the origins of these rocks have been solved.

CHAPTER III

DESCRIPTIVE GEOLOGY

INTRODUCTION

The geology of the Cuthbert Lake section is discussed in this chapter, with special attention focussed on the dyke swarm in the area. The Moak Lake ultrabasic body is considered with reference to this dyke swarm.

AREAL GEOLOGY

GENERAL CHARACTER OF THE AREA

The Thompson Lake-Moak Lake area lies entirely within the drainage basin of the Nelson River. The Nelson River flows past the southeast corner of the map-area. The relief of this area nowhere exceeds 200 feet, and the average elevation is 600 feet. Two tributaries of the Nelson River, the Burntwood and the Grass rivers, drain the area. These flow into the Nelson River at Split Lake, past the northeast corner of the map-area. The Manasan River flows into the Burntwood just west of Thompson Lake, and the Odei River, which drains Moak Lake, enters the Burntwood River just to the northeast of the map-area. The Grass River flows

diagonally across the area from the southwest corner to the east-central side. Paint Lake, Partridge Crop Lake, and Natawahunan Lake are large irregular expansions of the river. The drainage relationships are shown in Figure 1.

The large lakes and rivers of the area have rocky shorelines, with weeds and swamps in places forming sizeable portions. Numerous small lakes dot the map-area, but these, coupled with the small creeks and streams, present for the most part a swampy environment.

GLACIAL GEOLOGY

Glacial material covers most of the area, forming a gently rolling to flat surface. Boulders of Precambrian rock are present in these deposits but are rare. Glacial striae, where observed, indicate the direction of ice movement to be westerly; the azimuth of the striae ranging from 80 degrees to 90 degrees.

The most dominant feature of the topography is a series of well-defined moraines rising several hundred feet above the surrounding country. These trend northeast just north of Moak Lake, and extend southwest to Mystery Lake, where they cover much of the west and southwest part of the area back from the lake. These ridges are composed of boulder clay and gravel. Some of the gravel is suitable for use in the construction taking place in the area. Diamond drilling has revealed that these ridges cover the bedrock

to a depth of 400 feet in places.

REGIONAL GEOLOGY

Data concerning the regional geology of the Cuthbert Lake area have been derived in part from Dawson (1952) and in part from field work done by J. M. Patterson and the writer during the summer of 1958.

Sedimentary gneisses predominate in the northern part of the Thompson Lake-Moak Lake area. The gneisses are well banded and are composed of feldspar and quartz with minor biotite, hornblende and other accessories. The gneisses contain numerous bands of amphibolite and veins of pegmatite. Accompanying the gneisses is a belt of sediments, metamorphosed to the amphibolite facies, extending from Ospwagan Lake (Dawson, 1952) in the southwest part of the area to Mystery Lake. Quartzite, argillite, greywacke, and iron-formation are all represented in this belt in varying amounts.

Minor amounts of volcanic rocks of andesitic or basaltic composition were found along the Burntwood and Odei rivers in the northeast corner of the map-area. Alcock (Dawson, 1952) reports that a narrow belt of greenstone extends from Ospwagan Lake to Mystery Lake. Evidence for this greenstone was not found in the vicinity of Mystery Lake.

Intrusive rocks of the area include granite and gabbro. Both rock types appear to follow the primary structural features of the area. Peridotite with associated pyroxenite

phases is found in a long narrow belt from Moak Lake through Mystery Lake and past Ospwagan Lake. Peridotite in diamond drill core was found by the writer along the northeast part of the Burntwood River. Basic dykes are rare in the area except in the region of the Cuthbert Lake dyke swarm.

According to Dawson, the southwest part of the map-area is occupied by sedimentary gneisses intruded by granite.

LOCAL GEOLOGY

The "peridotite dykes" of the Cuthbert Lake section range in composition from peridotites to basic gabbros. In this report, however, they are referred to as peridotite dykes except where otherwise designated.

The rocks enclosing the Cuthbert Lake dyke swarm are a complex mixture of orthogneiss and paragneiss intermixed with metamorphosed basic rocks and recognizable sedimentary rocks. These rocks are intruded by the Cuthbert Lake dyke swarm which in turn are believed to be intruded by a series of olivine diabase dykes.

As the writer was more concerned with the basic and ultrabasic dykes of the area, these will be treated in much greater detail than the other rock types.

Table of Formations

The following table of formations was generally out-

lined by Dawson (1952). Field work in the Cuthbert Lake area by J. M. Patterson and the writer during the summer of 1958 confirms the relationships between the rock types as they are presented. The relation between the sediments and paragneiss is speculative because exposures of these rock types in contact were not seen. However, both rock types appear to conform closely to regional structural trends. Also, quartzite and limestone were the only sedimentary rocks seen. Both types would be expected to remain as separate entities under regional metamorphism which would convert more argilaceous rocks to paragneiss.

TABLE OF FORMATIONS

Pleistocene	Glacial moraine and glacial clay
	Erosional Contact
Precambrian	Olivine diabase dykes
	Intrusive Contact
	Peridotitic and associated basic dykes
	Intrusive Contact
	Plagioclase amphibolite
	Intrusive Contact
	Orthogneiss and associated pegmatite dykes
	Intrusive Contact
	Paragneiss, crystalline limestone, quartzites

Paragneiss

This rock type is predominant in the area. It is intruded by acid and basic rocks. A characteristic of the paragneiss is the presence of a pyroxene, usually hypersthene, in amounts commonly not exceeding 20 per cent. The presence of pyroxene in these rocks indicates that the area was subjected to regional metamorphism of the upper amphibolite or pyroxene-granulite facies.

In hand specimens, stubby grains of feldspar sometimes give these rocks a distinctive granular texture. In thin section, these rocks possess a definite recrystallized texture with most minerals present as anhedral grains. Pyroxene and feldspar in places form subhedral grains.

The surface of these rocks is pitted in many places, due to the weathering out of pyroxene or its alteration products. The pits are generally small, round, or slightly elongated; and distinct from those formed by the weathering out of long, narrow lenticles of biotite and hornblende. On the surface the rock ranges from moderately well foliated to massive. Compositional banding is present in some outcrops. Basic clots of biotite and hornblende with 50 per cent or less plagioclase are common. These clots average approximately 6 feet in length.

As previously mentioned, pyroxene is a characteristic mineral in these rocks. Light, greyish-brown feldspars that

give the rock a distinctive colour are common. Flesh coloured or white feldspar is also present. Large feldspar metacrysts as much as ½ inch long occur but are rare. Thin sections of the rock show that the quartz content varies considerably but is never greater than 50 per cent. The mafic minerals compose between 15 and 20 per cent of the specimens. A percentage composition of an average specimen of this rock type, as estimated visually from a thin section by J. M. Patterson (personal communication) is as follows.

Plagioclase (An 25-35).	55%
Quartz.	30%
Hypersthene	12%
Accessories	3%

Common accessories are biotite, hornblende, magnetite, pyrrhotite, calcite, zoisite, apatite, garnet, and potash feldspar. Accessories, with the exclusion of biotite and hornblende which are major constituents in some rocks, rarely exceed 5 per cent of the specimens.

This rock type is believed to be of sedimentary origin. Evidence for this conclusion is the variable composition of different bands of the rocks. Some bands contain a very high percentage of quartz, the origin of which is highly improbable by other than sedimentary means. Bands are usually distinct and are conformable with the strike. They are commonly marked by the development of garnet. These bands are believed by the writer to be remnant sedimentary structures.

Crystalline Limestone

Only minor outcrops of limestone are found in the Cuthbert Lake area. The outcrops are characterized by a very roughly weathered, massive appearance. They are all a dirty black to brown colour on the weathered surface. None of the visible outcrops are extensive. The majority are narrow bands, up to 30 feet wide, which conform to the strike of the enclosing rocks. They are usually interbedded with gneiss which contains quartz, plagioclase and hornblende.

Olivine and spinel are readily visible on the fresh surface and in places spinel is prominent on the weathered surface. Minerals found in thin sections of the limestones are, in order of abundance: calcite, olivine, spinel; and, in some specimens, phlogopite. Olivine generally shows partial alteration to serpentine.

Dawson (1952) gives two analyses of limestone from an occurrence on Natawahunan Lake. These are reproduced in Table I.

Dawson's interpretation is that this rock was originally a dolomite or magnesian limestone with small amounts of clayey and sandy impurities. This interpretation is consistent with the other occurrences of limestone seen by J. M. Patterson and the writer.

TABLE I

Analysis of Crystalline Limestones
in the vicinity of Cuthbert Lake

--	I	II
CaO.	33.36%	30.91%
MgO.	18.41%	19.75%
SiO_2	14.46%	14.20%
Al_2O_3 and Fe_2O_3	3.00%	5.63%
CO_2 and H_2O.	29.80%	29.30%

From Dawson (1952)

Quartzite

Occurrences of this rock type in the Cuthbert Lake area are evenly distributed, but rare. The rocks range in appearance from massive to slightly granular. Most quartzites contain approximately 85 per cent quartz, with additional small amounts of feldspar, muscovite, and biotite. Epidote and zoisite occur as accessories. Riebeckite, calcite, and sulphides are minor constituents in one thin section.

Orthogneiss

This rock type occurs interbanded with the paragneiss and plagioclase amphibolite. The gneissocity of the rock corresponds to the regional attitudes, indicating that they were emplaced before the cessation of regional metamorphism.

These rocks are granitic in appearance and possess a

more igneous texture than the paragneiss. The sheared appearance common to these rocks is due, primarily, to the altered and elongated appearance of the mafic minerals.

The orthogneiss contains approximately 15 to 20 per cent mafic minerals composed primarily of biotite and chlorite. Thin sections of these rocks show that they contain varying percentages of quartz; 30 per cent being found in thin sections from some outcrops. Feldspar is usually of two types. One is microcline and the other is an antiperthite or a sodic oligoclase. Biotite is the primary mafic mineral but chlorite and hornblende are present in places. Accessory minerals include apatite, magnetite, and clinozoisite.

Several pegmatite dykes consisting of very coarse-grained feldspar, some biotite, and quartz are found in conjunction with the granitic gneisses. They cut the orthogneiss and probably represent a late intrusive phase of the granite. Commonly they are sheared, which indicates that they were intruded before metamorphism of the area had ceased.

Plagioclase Amphibolite

Rocks of this type are extensively developed in the area that was mapped and form, in places, mappable units. They also occur in great quantities as clots within the orthogneiss and paragneiss. These clots are small, very

irregular in shape, and are too small to be shown in the map. These rocks consist almost entirely of plagioclase and amphibole in approximately equal proportions, although pyroxene is present in some outcrops. Elongated amphibole grains give the rock a lineation but the plagioclase usually has a granular appearance.

Some of the large units of the plagioclase amphibolite have been interpreted by Dawson (1952) as being metamorphosed gabbro intrusions. However, the extensive development of these rocks as clots within the gneisses indicates that they might represent the development of sills and lava flows, subsequently metamorphosed. One observation suggesting that these rocks might once have been sills is their concordant nature with the enclosing rock and the lens shaped character of their outcrop. Contacts with the host rock are also sharp and well defined.

Basic Dykes

Numerous basic dykes are present in the Cuthbert Lake area. They represent two periods of intrusion. The first period consists of ultrabasic dykes with numerous related basic dykes, which transect the regional structure almost at right angles. This set is cut by a younger set of olivine diabase dykes, which conform, in general, to regional attitudes. Very few dykes of this set were seen, but their intrusive nature with respect to the first set was established.

Both sets of dykes were intruded later than the regional metamorphism of the area as all are relatively unmetamorphosed. These dykes will be described in detail in the sections to follow.

STRUCTURE OF THE CUTHBERT LAKE SECTION

INTRODUCTORY STATEMENT

This section describes the structure of the basic and ultrabasic dykes in the Cuthbert Lake area. An attempt is made to show how the structure of the enclosing rock has controlled the emplacement of the peridotitic complex.

SETTING

The Cuthbert Lake lineament is a prominent feature of the Thompson Lake-Moak Lake area. This topographic lineament, which has an average strike of north 28 degrees east, extends from Cuthbert Lake in the south, through Natawahunan Lake and Buckingham Lake, to Begg Lake in the north. This gives an approximate length of 24 miles to the lineament. The last three of the above mentioned lakes are elongated in a general easterly direction, corresponding to the strike of the regional structure. The lineament is, however, very prominent through Cuthbert Lake and through the creek joining

Cuthbert Lake to Natawahunan Lake, as both lie along it. Although it is still obvious, the lineament is not as strongly marked through Natawahunan Lake. Between Natawahunan Lake and Buckingham Lake is a small lake which empties into Buckingham Lake via a small creek. This lake is elongated in the direction of the lineament and both the lake and the creek form a portion of the feature. Begg Lake empties into Buckingham Lake by way of a narrow meandering creek. This creek forms the northern part of the lineation.

Dawson (1952) stated that this lineament is due to the presence of a peridotite dyke. The peridotite, being much softer than the enclosing rock, weathered much more easily, and is now marked by a series of waterways. Dawson considered the erosion of the dyke to have played an important part in the formation of the drainage of the area.

Dawson also presented evidence that this dyke extends past the southern tip of Cuthbert Lake to Wintering Lake (Dawson, 1952, page 16):

> "This dyke, although largely drift-covered in the southern part, appears to have a continuous length of more than 40 miles and is somewhat less than ¼ mile in average width..... The dyke extends from the southeastern bay of Wintering Lake through Paynter, Cuthbert,.....and Begg Lakes."

The writer did not work south of Cuthbert Lake. However, on the basis of the mapping done in the Cuthbert Lake area, it is considered highly improbable that a contin-

uous peridotite dyke is associated with the lineation, even though the lineation may extend for the length described by Dawson.

The distribution of the peridotite does indicate that it is in a dyke-like form, even though contacts between it and the gneiss are not visible. The fact that fresh peridotite is found in the area only along the Cuthbert Lake lineament is significant. Because this lineament cuts the strong regional structural trend at approximately right angles, it is necessary to assume that the peridotite has been intruded in the form of a dyke.

DESCRIPTION OF THE PERIDOTITE

General Characteristics

The peridotite outcrops are distinctive in the field. They have a dark brown to black weathered surface, which is generally pitted due to the weathering out of constituent minerals. At first sight, the rock appears to be very fine grained. The rock is extremely tough and hard to break with a hammer. The peridotite is composed almost exclusively of mafic minerals.

The shape of the outcrops is also distinctive. They are usually low, no more than 6 feet above water; although some were found which were close to 20 feet above water level.

The outcrops are commonly smoothly rounded, rising gently from the water to the highest part of the outcrop. They are usually elongated in the general direction of the lineament.

The size of the outcrops ranges from 4 feet by 5 feet to 1500 feet by 60 feet. The widest outcrop was 140 feet measured perpendicular to the average strike of the lineament.

The detailed petrology of the peridotitic complex will be discussed in a later section.

Description of the Joint Sets

Joints developed in the peridotite outcrops are the only consistent structural feature noted in these rocks. In each outcrop, at least one set of joints is prominent; in some outcrops, 2 sets of joints are well developed; in others, up to 4 sets of joints are present.

Balk (1948) discussed joint sets which are developed during the cooling of an igneous dyke. He stated that cross joints are developed perpendicular to the walls of the intrusion. They are longer and straighter than other joints and are often recognizable by their remarkable persistance and evenness. They are among the first fractures to form in a congealing igneous mass and often have a coating of hydrothermal minerals on the joint surfaces. It is by the separation of cross joints that the igneous body is lengthened on cooling. Balk stated that cross joints can only be

identified by the presence of flow lines which are perpendicular to the joints. If flow lines are not visible, cross joints as such cannot be distinguished, although corresponding fractures may exist.

Balk described longitudinal joints as joints whose strike is parallel to the trend of the flow lines. Flow lines, in turn, develop parallel to the walls of the dyke. They introduce an element of mechanical weakness into the rock fabric and therefore fractures embracing these lines form relatively easily. It is these fractures which are the longitudinal joints. Longitudinal joints differ from cross joints in that they are rougher and lack the clean-cut, smooth surfaces of the cross joints. Longitudinal joints also tend to develop zones in which they are closely spaced.

In describing joints formed in an igneous dyke, Lahee (1952) said that tension joints are equivalent to cross joints, but their relationship to the true cross joints must be established in order that the term "tension joint" can be used. He pointed out that cross joints differ from tension joints in having associated flow lines, and that joints formed by tension in the cooling of a dyke can lie in various plane directions perpendicular to the wall of the dyke.

The joint sets in the outcrops of the peridotitic complex in the Cuthbert Lake area are of several distinct types. These sets could be distinguished on the outcrop by their attitudes and by their characteristic appearance.

One set of joints present in the outcrops can be distinguished on the basis of its regularity. This set has a strike which is roughly perpendicular to the strike of the Cuthbert Lake lineament and dips steeply to either the south or the north. Joints of this set are very prominent on the outcrop. They are wide and usually planar over the width of the outcrop. These joints are spaced from 3 to 15 feet apart on most outcrops.

A second set of joints is also present on most peridotite outcrops. These joints are characterized by the fact that they strike approximately parallel to the strike of the Cuthbert Lake lineament. These joints always dip steeply in either an easterly or westerly direction. Another characteristic of the joints of this set is that they are very closely spaced. In some outcrops, these joints were found to be spaced no more than 1/8 inch apart. Joints of this set are more irregular and not as continuous as those in the set previously described.

Other joint sets are found in conjunction with the peridotite outcrops. One set, present in some outcrops, strikes parallel to the first set of joints described above. This joint set has a much shallower dip than the first set and is poorly defined. Another poorly defined joint set has a strike roughly parallel to the Cuthbert Lake lineament. In this respect it is similar to the second joint set; however, the dip of these joints is much shallower than that

of the second set. On some outcrops a joint set roughly bisects the angle made by the first two sets of joints described in this section. This set is generally steeply dipping and poorly defined. Joints of this type were regarded by Lahee (1951) as being shear planes produced by a compressional force normal to the trend of the flow lines in the dyke. This diagonal joint set is present in only some of the peridotite outcrops.

Distribution of the Peridotite

The outcrops of peridotite in the Cuthbert Lake area are distributed discontinuously but evenly throughout the length of the lineament. Several small outcrops occur removed from the immediate vicinity of the lineament but these are rare.

Peridotite was seen in contact with the enclosing gneiss in only two places. One occurrence was found at the north end of Cuthbert Lake on the west shore. There, a peridotite dyke approximately 25 feet wide is exposed in contact with the enclosing gneiss for a length of 2 feet. Elsewhere along this exposure, the contact was obscured. The second occurrence is on the north shore of Natawahunan Lake where two peridotite dykes, each with an exposed width of approximately 5 feet, flank a narrow strip of gneiss approximately 3 feet wide. The exposed contact on each dyke

is approximately 10 feet in length. Other outcrops of peridotite occur as islands or as isolated outcrops along the shore so that attitudes for contacts were not available except in the above mentioned places.

The geological map, drafted on a preliminary scale of 1 inch equals 1000 feet, shows a definite distribution of the peridotite outcrops. This distribution takes the form of a series of small dyke segments arranged in an "en echelon" pattern along the length of the lineament. The dyke segments, proceeding from north to south, are offset to the west with respect to each other and, in general, have a more northerly strike than has the main lineament.

A study of the joint pattern was undertaken to test the validity of this apparent distribution.

To understand the basis of a study of this nature, it is necessary to understand the relationships which exist between joint sets in a dyke which has been subjected to ideal cooling. During the ideal cooling of a dyke, a longitudinal joint set forms parallel to the walls of the dyke and several tensional joint sets form at right angles to the walls of the dyke (Balk, 1948). These tensional joint sets can lie in any plane perpendicular to the walls of the dyke, depending on the forces acting in the dyke during the cooling process.

For a dyke which has undergone ideal cooling, all tensional joint sets will be perpendicular to the longitudinal

joint set. When these sets are plotted on a stereographic net, the pole to the longitudinal joint set will lie on the line of intersection of any two or more tensional joint sets present in the dyke. Therefore, the longitudinal joint set can be identified as the set of joints whose pole corresponds to the line of intersection of the tensional joint sets. Thus, for an outcrop revealing no contacts, if one joint set can be identified as a longitudinal set, the attitude of the dyke or dyke segment of which it is a part can be determined.

Possible dyke segments were isolated by studying the distribution of peridotite outcrops with respect to those of the enclosing gneiss. The joint sets in the outcrops comprising each suspected segment were plotted on a stereographic net. In general, one set of joints for each segment proved to be common to all the outcrops comprising a particular segment. The pole to this set was found to lie within a cone with a radius of 15 degrees from the line of intersection of other joint sets present in the segment. The attitudes of all the longitudinal joints in the dyke segment were then averaged. The resulting attitude was assumed to be the average attitude of the dyke segment. This value for all the dyke segments analyzed appears on the map accompanying this report. Thus, by comparison of the actual joint set distribution to that of an ideal case, one set of joints was shown to be a longitudinal joint set. The remaining joint sets whose line of intersection corresponded to the pole of

the longitudinal joint set were shown to be tensional joints.

In Figures 2, 3, 4, and 5, the joints for each outcrop of a typical dyke segment are shown as they are plotted on a stereographic net. In these diagrams, the longitudinal joint set strikes at approximately north 25 degrees east. The pole to this set lies close to the line of intersection of sets of joints whose strike is about 90 degrees to the longitudinal joint set. Figure 6 shows the close correspondence between poles of the longitudinal joints and the average attitude of the tensional joints of the dyke segment represented in the preceding figures. Joint sets of the other dyke segments were treated in a similar manner, and the same relationship between the joint sets was evident.

It may be noted that by a comparison of the physical appearance of the joint sets on the outcrops to the descriptions of joints as given by Balk and Lahee and previously recorded, longitudinal joint sets could have been established. However, this was not a sufficient means by which to identify these joints. Without confirmation of how closely the joint sets of the dyke segments correspond to the ideal case, no conclusion could be drawn as to the attitude of the individual dyke segments. It had to be determined that the joint sets were essentially free from later deformation and that they formed in close to ideal conditions. A comparison of the ideal system to the actual one as found in the field enables the joint sets to be designated with certainty.

FIGURE 2

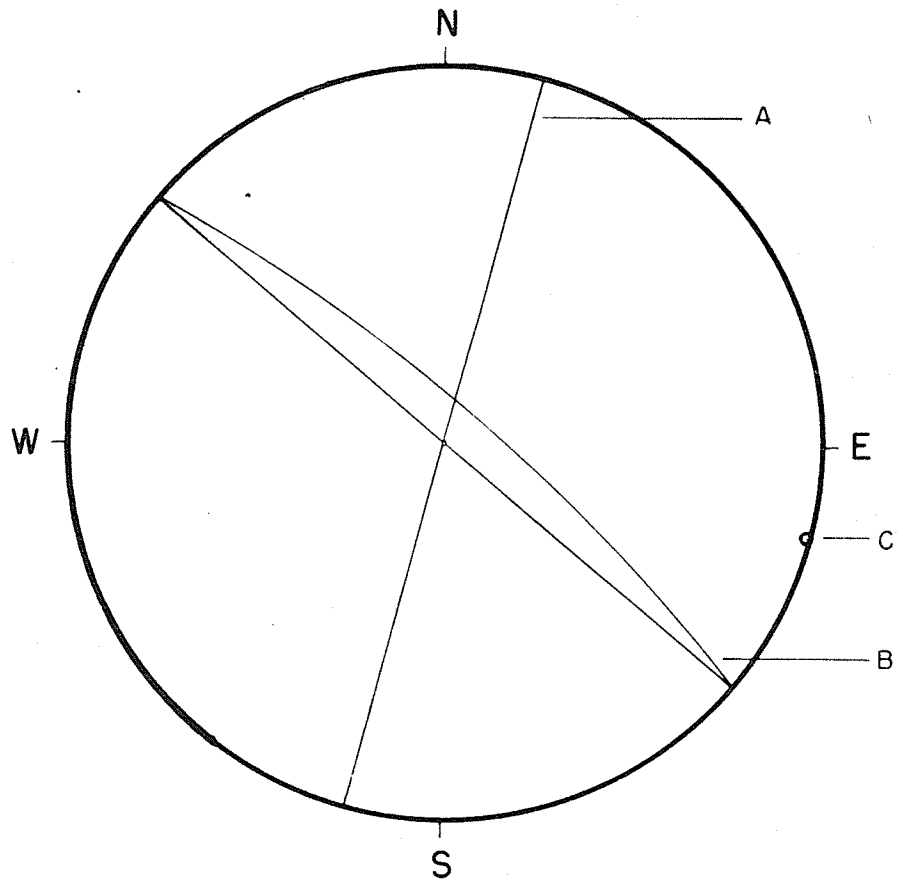


DIAGRAM OF JOINT SETS FOR LOCATION "A"

Joint sets are plotted on a stereographic net.

A. Longitudinal joint. Strike - north 15 degrees east. Dip - vertical.

B. Tensional joint. Strike - south 50 degrees east. Dip - 80 degrees northerly.

C. Pole to longitudinal joint.

FIGURE 3

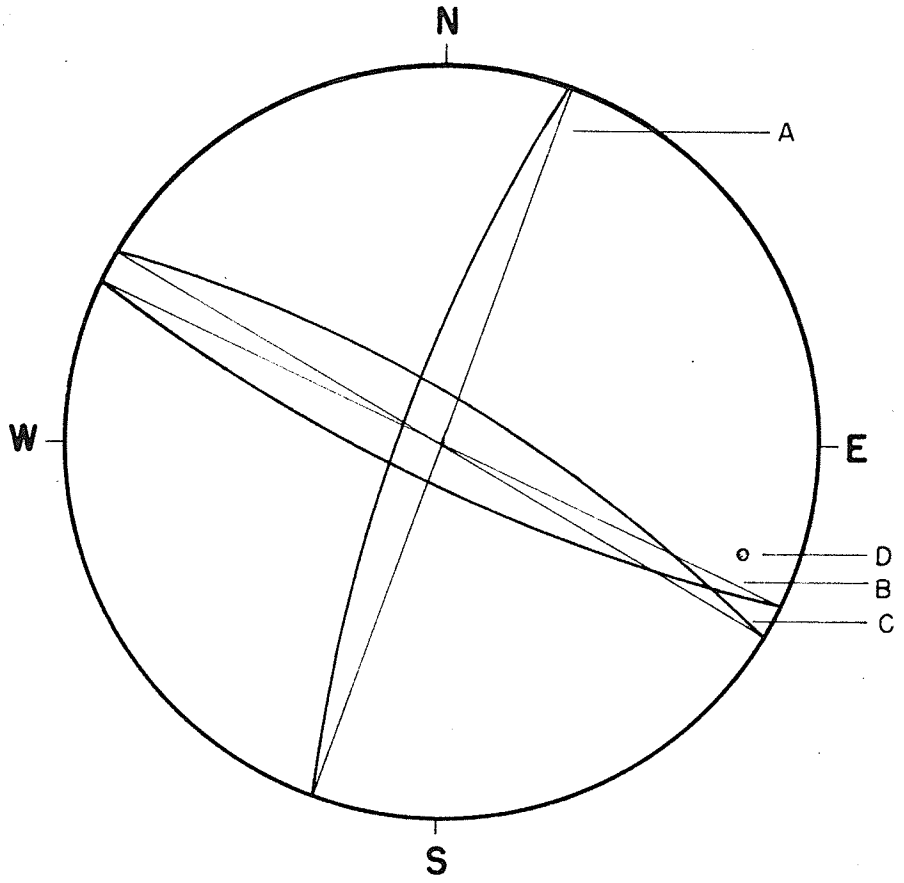


DIAGRAM OF JOINT SETS FOR LOCATION "B"

Joint sets are plotted on a stereographic net.

A. Longitudinal joint. Strike - north 20 degrees east. Dip - 80 degrees westerly.
B. Tensional joint. Strike - south 65 degrees east. Dip - 80 degrees southerly.
C. Tensional joint. Strike - south 60 degrees east. Dip - 75 degrees northerly.
D. Pole to longitudinal joint.

FIGURE 4

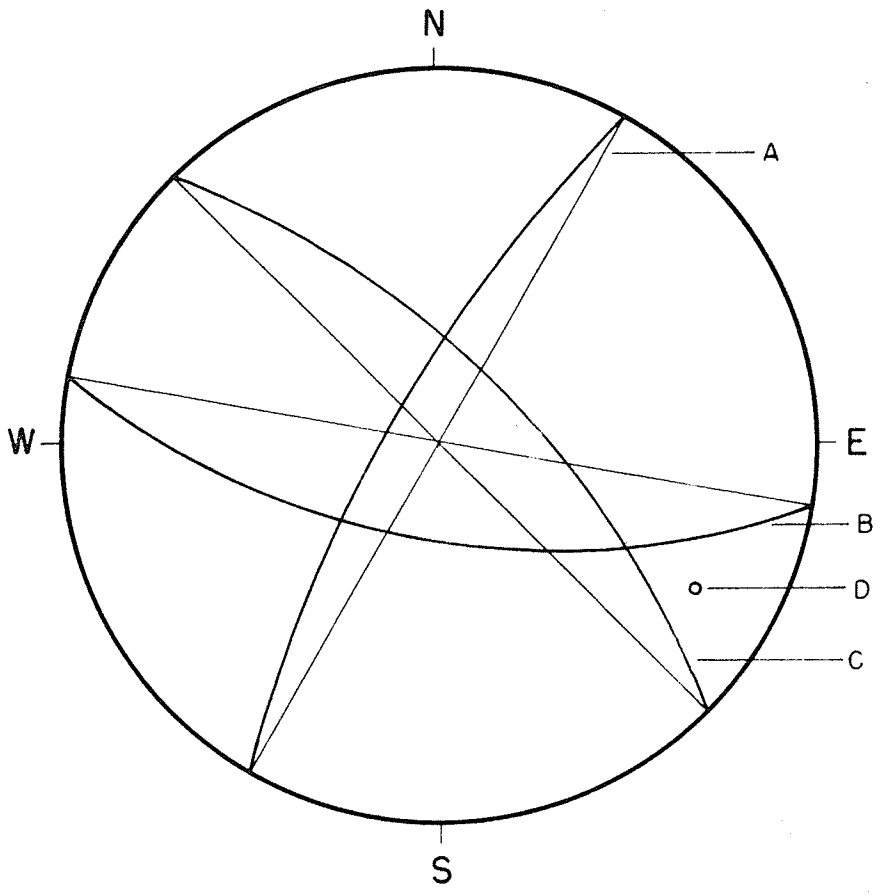


DIAGRAM OF JOINT SETS FOR LOCATION "C"

Joint sets are plotted on a stereographic net.
A. Longitudinal joint. Strike - north 35 degrees east. Dip - 75 degrees westerly.
B. Tensional joint. Strike - south 70 degrees east. Dip - 60 degrees southerly.
C. Tensional joint. Strike - south 45 degrees east. Dip - 65 degrees northerly.
D. Pole to longitudinal joint.

FIGURE 5

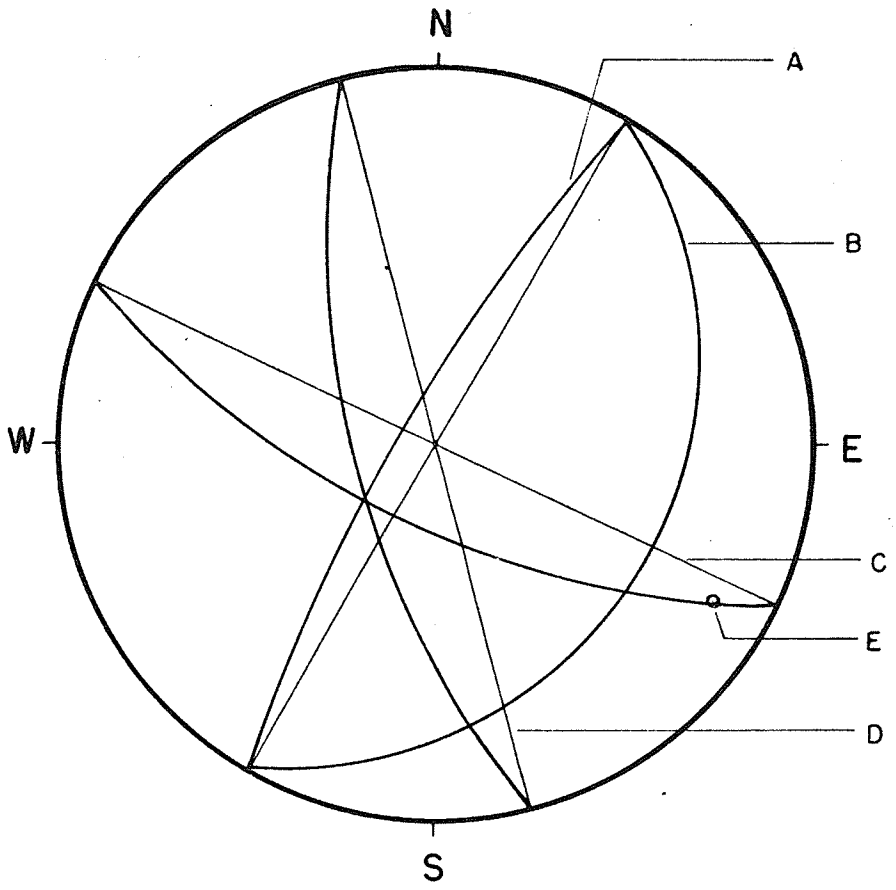


DIAGRAM OF JOINT SETS FOR LOCATION "D"

Joint sets are plotted on a stereographic net.

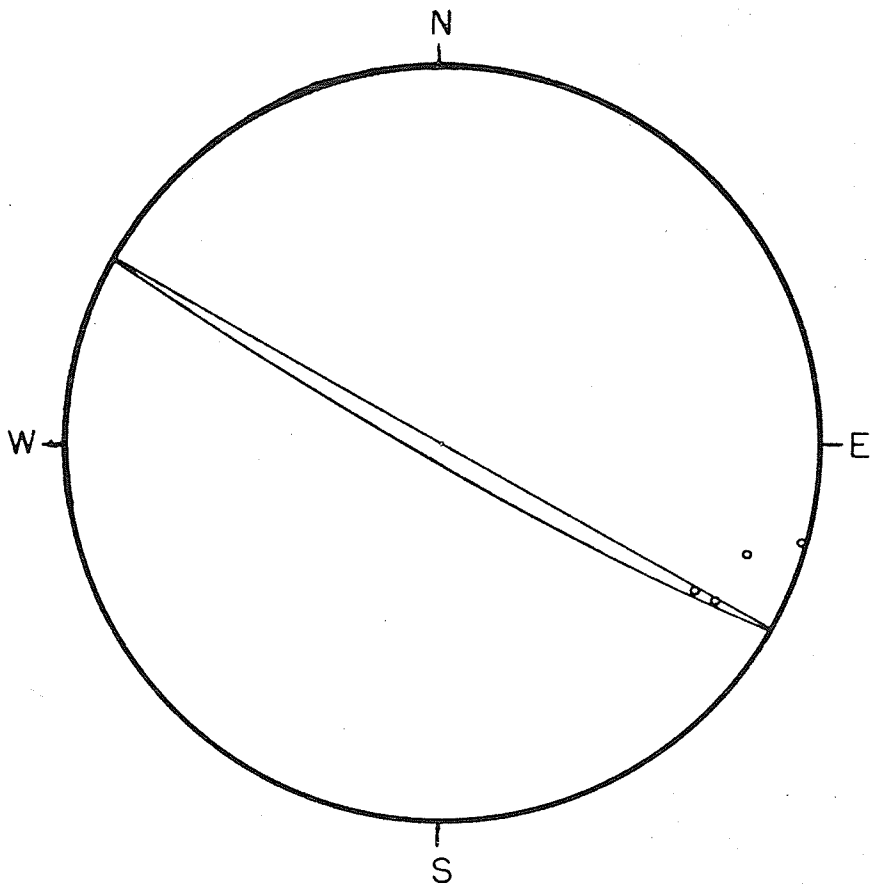
A. Longitudinal joint. Strike - north 30 degrees east. Dip - 80 degrees westerly.
B. Secondary longitudinal joint. Strike - north 30 degrees east. Dip - 25 degrees easterly.
C. Tensional joint. Strike - south 65 degrees east. Dip - 65 degrees southerly.
D. Shear joint. Strike - south 15 degrees east. Dip - 65 degrees westerly.
E. Pole to longitudinal joint.

It was found that not all the peridotite outcrops could be fitted into a postulated dyke segment. These outcrops are therefore not included in the segments shown on the map.

It was also found that there are joints present in the peridotite which are obviously neither longitudinal or tensional joints. These may be shear joints which are poorly developed in the outcrop and which approximately bisect the angle between the longitudinal and the tensional joints.

Because of the close degree of correspondence between the joint sets on the peridotite outcrop and those which would form in an ideally cooled dyke, it may be assumed with a reasonable degree of certainty that the postulated dyke segments do exist and that they exist as essentially planar features. In an analysis of the dyke segments, some variation in the attitudes of the longitudinal joints was noted. This could be explained by variations in the stress field in which the joints formed as the dyke magma cooled. It is also possible that the surfaces of the dyke segments are not planar but are slightly undulating. The difference in the attitudes of the longitudinal joints could be a reflection of this undulating surface. It is probable that the variation in the attitudes of the longitudinal joints is due to a combination of these two possibilities.

FIGURE 6



RELATION BETWEEN POLES TO THE LONGITUDINAL JOINTS AND THE AVERAGE TENSIONAL JOINT PLANE

Circles indicate the position of poles to longitudinal joints from locations "A", "B", "C", and "D" as plotted on a stereographic diagram. The plane represents the average of the tensional joint planes from the above locations.

Distribution of the Peridotite

Dawson (1952) indicated that the peridotite in this area forms a continuous dyke. To be continuous, the peridotite would necessarily be branching and extremely sinuous. The writer has established the presence of individual dyke segments as shown on the map accompanying this report. These segments are arranged in an "en echelon" pattern over the length of the lineament in the Cuthbert Lake area. The outcrops of peridotite which are not included in any of the dyke segments have longitudinal-type joints roughly parallel to the main lineation of the area. It is statistically doubtful that any changes in the strike of the longitudinal joints, which might indicate a sinuous character to the peridotite, would not have been found. The absence of any such portions of the dyke is a strong indication that the peridotite is not continuous but that it exists as a number of individual dyke segments as shown on the map. The possibility is not discarded that dyke segments may be united at depth or that they may be joined by very narrow veinlets of dyke material, as in some basic dykes yet to be described. However, the writer does not believe that the peridotite is continuous in the sense implied by Dawson (1952): that its width remains relatively constant throughout the length of the lineament.

DISTRIBUTION OF THE ASSOCIATED DYKE SWARM

Associated with the peridotite dyke segments are hundreds of basic dykes ranging in composition from basic gabbros to diorites. These dykes range in width from 1 inch to 400 feet, the average width being approximately 15 feet. Very few dykes exceeding 100 feet in width were found.

During the course of the field work in the Cuthbert Lake area, attitudes were recorded for 276 dykes. An equal number of dykes were seen whose attitudes were not taken.

The extent of this dyke swarm is approximately known. It most certainly extends to the east and south of the Cuthbert Lake area because numerous dykes have been recorded in these areas by Dawson (1952).

The Sipiwesk map sheet (Harrison, 1951) shows a remarkably straight portion of the Nelson River over a distance of about 40 miles. The lineation strikes north 20 degrees east and lies 24 miles east of the Cuthbert Lake lineament. In 1877, Bell(Dawson, 1951) reported that a peridotite dyke underlies this area. G. C. Milligan (personal communication), who aided in the reconnaissance mapping of the Sipiwesk area, reported that east of the northerly-trending portions of the Nelson River, basic dykes are almost totally or totally absent. This includes the area of Dafoe, Cauchon and Goulet lakes as well as the south part of Sipiwesk Lake. Dykes are absent in the Utik Lake and Bear

Lake areas. However, towards the northeast part of Sipiwesk Lake and the outlet of the lake, dykes become more numerous. Milligan also reported that dykes are exceptionally numerous in Landing Lake. The eastern border of the dyke swarm appears to be the straight, northeasterly-trending part of the Nelson River. The southeastern boundary is indicated to be Sipiwesk Lake.

In the Split Lake area, Milligan (1956) reported that numerous basic dykes occur but that they are confined to the part of the area which lies south of the Split Lake-Setting Lake break.

In the Uhlman Lake area (Wright, 1953) and the Nelson House area (Quinn, 1955), both of which lie to the north and west of the Split Lake-Setting Lake break, basic dykes are either rare or absent. This break appears to form the northern boundary of the dyke swarm.

The writer found that the dyke swarm does not extend as far north as the Burntwood River. J. M. Patterson reports that the number of dykes decreases in the vicinity of Isbister Lake (personal communication). Dykes are a rarity in the Apussigamasi Lake area. It appears that the west boundary of the dyke swarm lies not far west of Isbister Lake, and presumably roughly parallels the Cuthbert Lake lineament.

To arrive at the predominating attitude of the dykes, the writer divided them into two groups: those lying to the

east and those lying to the west of the lineament. The poles to the attitudes of the dykes in each group were plotted on separate Schmidt net diagrams. These points were then contoured according to the procedure outlined by Billings (1942). The results are included in Figures 7 and 8.

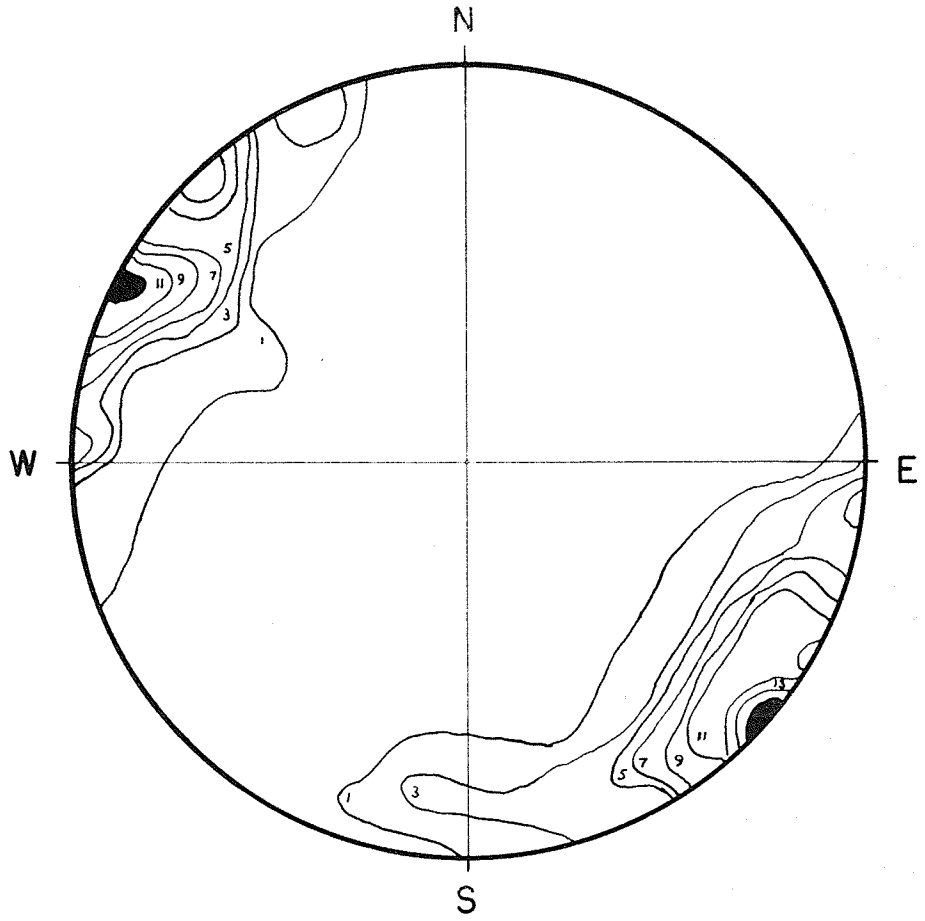
These figures show that the statistical concentration of the poles to the dykes on the west side and on the east side of the peridotite lies within the same area on the Schmidt net. The strike represented by the peak of the pole concentration in Figure 7 is north 30 degrees east, with a vertical dip. The corresponding strike for the peak shown in Figure 8 is north 30 degrees east with a dip of 72 degrees westerly. The similarity of the attitudes of the dykes on either side of the lineament is significant. Because of the distribution of the contour lines in the figures, the discrepancy in dip is not considered important. It is significant that poles to dykes do not occur in the northeast and southwest quadrants of either diagram. The similarity between the diagrams suggests that all the dykes belong to the same period of intrusion.

EMPLACEMENT OF THE DYKES

Peridotite Dyke Segments

A statistical analysis of the attitudes of the gneissocity of the enclosing rocks was undertaken to determine what

FIGURE 7

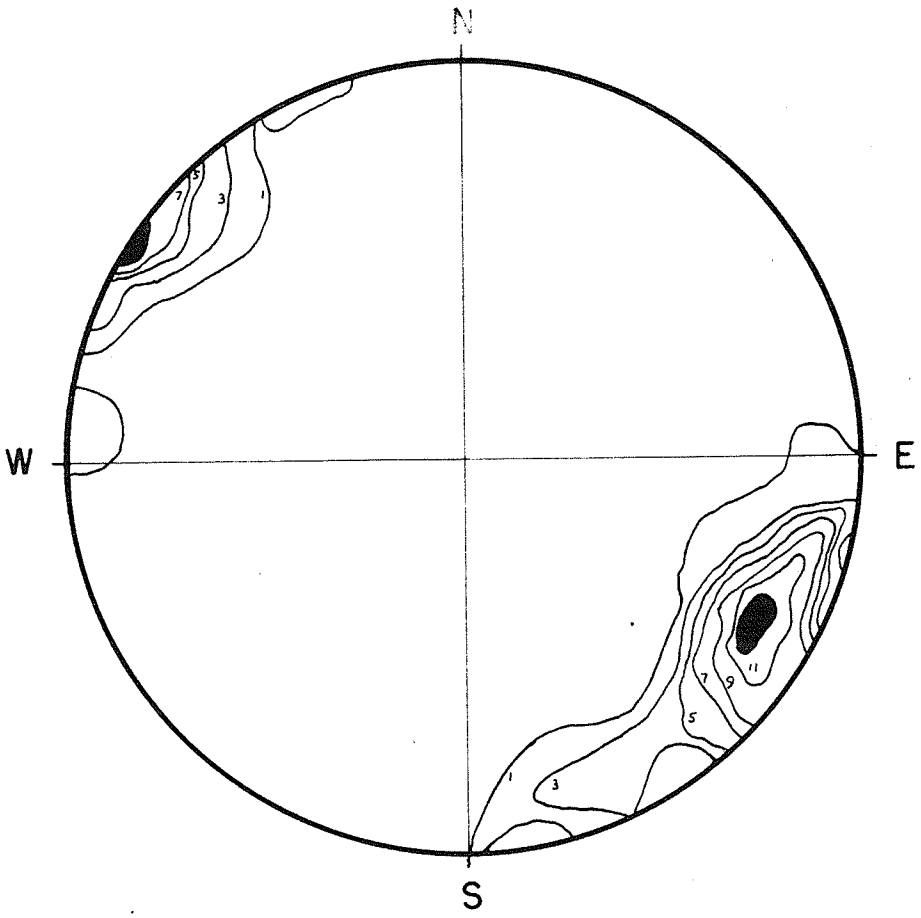


ATTITUDES OF DYKES WEST OF THE CUTHBERT LAKE LINEAMENT

This figure shows contours for 170 poles to attitudes of basic dykes plotted on a schmidt net. The major peak represents an attitude the strike of which is north 30 degrees east and the dip, vertical.

The 1% contour line is shown. The contour interval for the remaining contours is 2%.

FIGURE 8



ATTITUDES OF DYKES EAST OF THE CUTHBERT LAKE LINEAMENT

This figure shows contours for 106 poles to attitudes of basic dykes plotted on a schmidt net. The major peak represents an attitude the strike of which is north 30 degrees east and the dip, 72 degrees northerly.

The 1% contour line is shown. The contour interval for the remaining contours is 2%.

might have controlled the intrusion of peridotite into its present location.

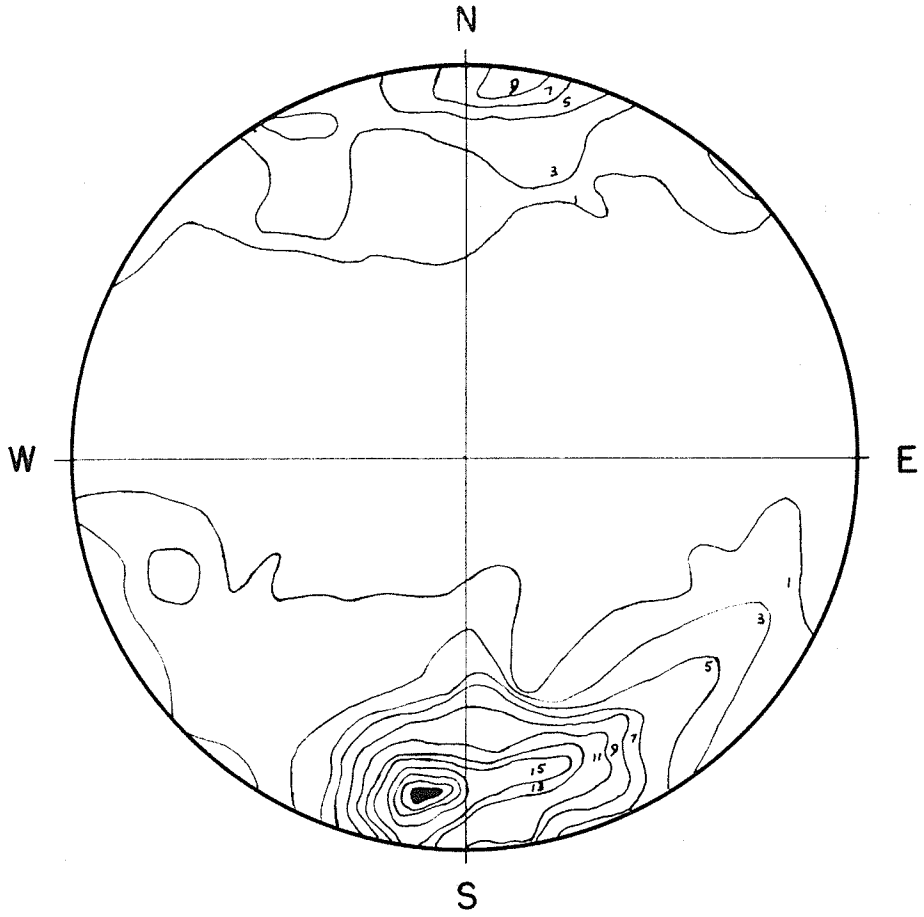
The poles to all the available attitudes of the enclosing rocks were plotted on separate Schmidt net diagrams. Poles to attitudes for rocks east of the lineament were plotted on one diagram and those for rocks to the west of the lineament were plotted on another diagram. The points representing the poles were then contoured to obtain the frequency distribution.

The results of this study are shown in Figures 9 and 10. The peak for the diagram representing the rocks to the west of the lineament corresponds to a strike of south 80 degrees east and to a dip of 78 degrees northerly. The peak on the diagram representing the rocks to the east side of the lineament corresponds to a strike of north 57 degrees east and to a dip of 72 degrees northerly.

Three features of these diagrams should be noted: the pronounced concentration of points; the complete absence of attitudes the poles of which lie in the central belt of each of the diagrams; and the discrepancy between the concentration peaks for the poles to dykes on either side of the lineament.

The large discrepancy in the attitudes on either side of the lineament at first suggested the possibility that the lineament was a fault along which rotational movement had taken place and that this fault was a zone of weakness along

FIGURE 9

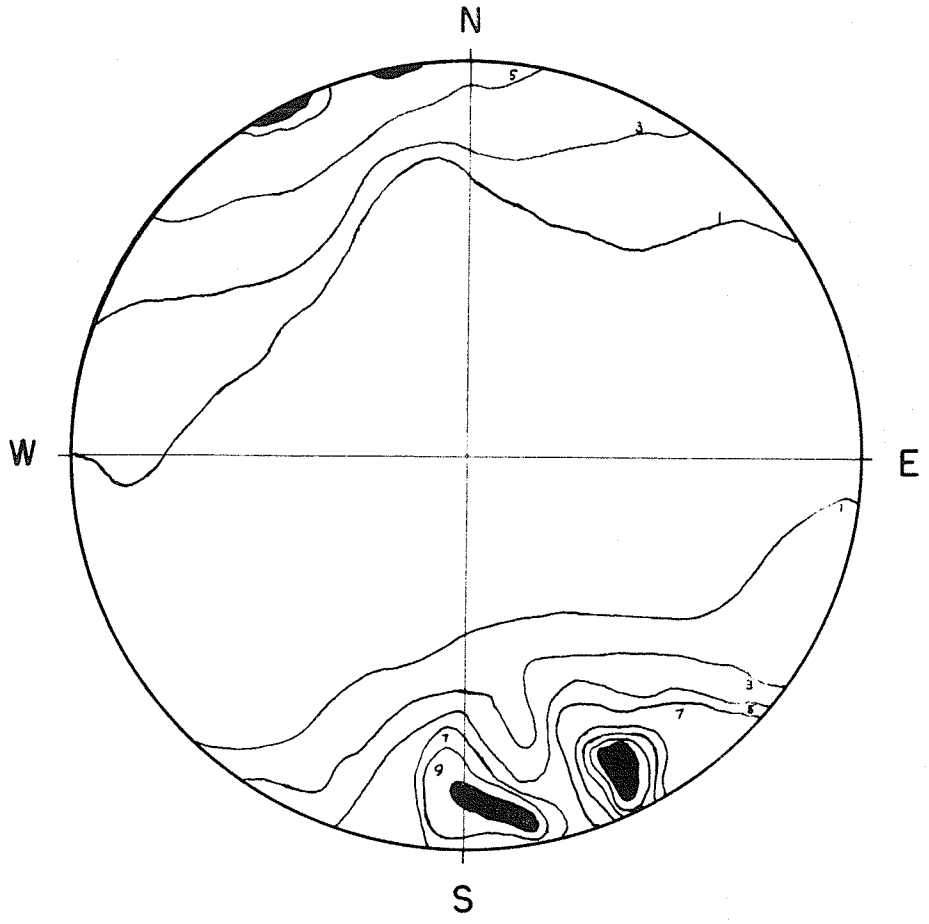


ATTITUDES OF THE GNEISSOSITY WEST
OF THE CUTHBERT LAKE LINEAMENT

This figure shows contours for 208 poles to the gneissosity of the country rock plotted on a schmidt-net. The major peak represents an attitude the strike of which is south 80 degrees east and the dip, 78 degrees northerly.

The 1% contour line is shown. The contour interval for the remaining contours is 2%.

FIGURE 10



ATTITUDES OF THE GNEISSOSITY EAST
OF THE CUTHBERT LAKE LINEAMENT

This figure shows contours for 145 poles to the gneissosity of the country rock plotted on a schmidt net. The major peak represents an attitude the strike of which is north 57 degrees east and the dip, 72 degrees northerly.

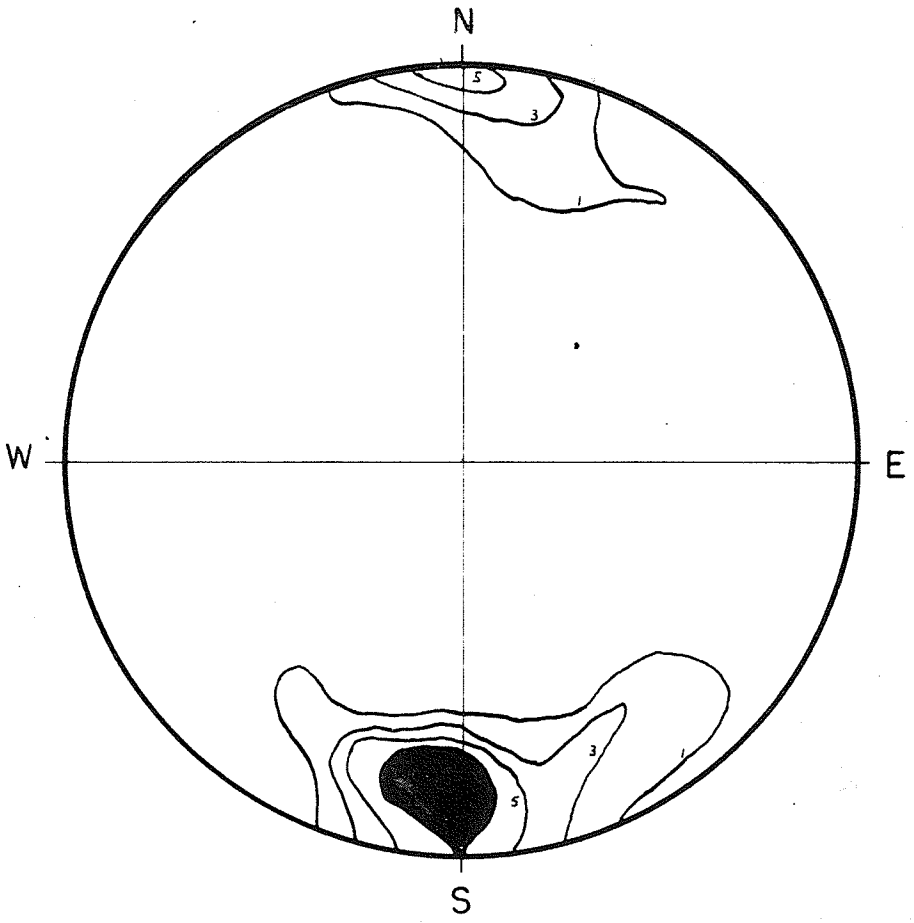
The 1% contour line is shown. The contour interval for the remaining contours is 2%.

which the peridotite had been intruded. However, the distribution of the segments of peridotite is not in accord with this idea. Consequently, Schmidt net diagrams were made showing the poles to the attitudes for the rocks which are immediately adjacent to the lineament. Separate diagrams were made for the rocks to the east and to the west of the lineament. The resulting contoured diagrams showing the frequency distribution of the poles are represented by Figures 11 and 12.

A very close degree of approximation is evident between the two figures. The attitude represented by the peak on the figure for the west side is south 86 degrees east, with a dip of 74 degrees northerly. The attitude represented by the peak on the figure for the east side is south 86 degrees east, with a dip of 72 degrees northerly. The difference between the two attitudes is negligible.

These results suggest that there has been no fault movement along the lineament. No movement directions seem feasible which would give the results found by the study of the attitudes. The writer believes that the discrepancy in attitudes shown between Figures 9 and 10 can be explained by the presence of a drag fold of regional dimensions in the area. The intrusion of peridotite was governed by a zone of weakness existing in this fold. This zone was opened when forces resulting in tensional strain acted upon the area. The fact that such a zone of weakness existed in the gneiss

FIGURE 11

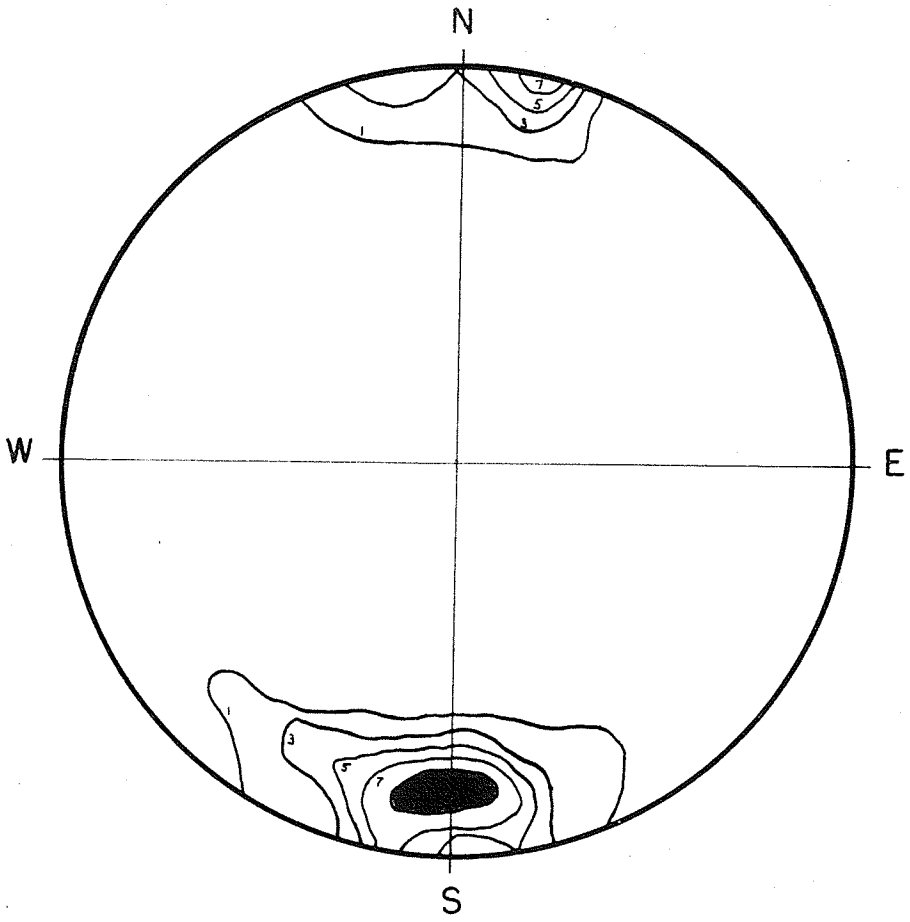


ATTITUDES OF THE GNEISSOSITY ADJACENT TO THE WEST SIDE OF THE CUTHBERT LAKE LINEAMENT

This figure shows contours for 86 poles to the gneissosity of the country rock lying immediately to the west of the Cuthbert Lake lineament. The poles are plotted on a schmidt net. The major peak represents an attitude the strike of which is south 86 degrees east and the dip, 74 degrees northerly.

The 1% contour line is shown. The contour interval for the remaining contours is 2%.

FIGURE 12



ATTITUDES OF THE GNEISSOSITY ADJACENT TO THE EAST SIDE OF THE CUTHBERT LAKE LINEAMENT

This figure shows contours for 85 poles to the gneissosity of the country rock lying immediately to the east of the Cuthbert Lake lineament. The poles are plotted on a schmidt-net. The major peak represents an attitude the strike of which is east 4 degrees south and the dip, 72 degrees northerly.

The 1% contour line is shown. The contour interval for the remaining contours is 2%.

is suggested by shearing in the gneiss adjacent and parallel to the lineament in some locations. Subsequent erosion has produced the present appearance of the lineation.

Associated Dyke Swarm

Billings (1942) and Anderson (1951) stated that dyke swarms are commonly caused by tension. This is a logical explanation for the origin of the dyke swarm in the Cuthbert Lake area. Only by a tensional force could a series of sub-parallel fractures form. The filling of these fractures by igneous rock material formed the dykes as they are now found in the field.

The attitude of the peridotite dyke segments also indicates that a tensional force has caused the opening of the fractures. Noble (1952) stated that an "en echelon" dyke pattern is possibly caused by tension fractures formed between opposed shear forces. The "en echelon" pattern of the peridotite segments conforms to this suggestion. However, not enough work was done in the area to enable the writer to propose what type of forces caused the tensional fractures or what the orientation of these forces might be.

Anderson (1951) stated that dyke fissures must be caused by tensional forces. These forces can be of two kinds: regional tensions, and tension caused by the wedging action of the intruding dyke magma.

There is evidence that both types of tensional forces have operated in the formation of the Cuthbert Lake dyke swarm. Many of the dykes show no evidence of deformation at all. These are massive in the centre and remain so out to their contacts. The writer considers the massive dykes to have originated as liquid magma, which welled up along fractures opened by regional tensional forces.

A minority of other dykes in the area show evidence of forcible injection, with a wedging action of the magma playing an important role in their emplacement. Several occurrences were found in which the dykes are massive in their interior. Their contacts, however, indicate shearing parallel to the walls. This shearing is thought by the writer to be a result of forcible intrusion. In one occurrence the end of a dyke was exhibited in plan view. Here, the gneiss was contorted around the end of the dyke. This phenomenon was considered by Noble (1952) to be evidence of forcible intrusion.

There is also evidence that the dykes have been intruded along zones of pre-existing weakness in the rock. In one occurrence a dyke 2 feet wide abuts against a shear zone in the gneiss which strikes at right angles to the strike of the dyke. The main part of the dyke stops at the shear zone, but a narrow veinlet of dyke material 2 inches wide follows the shear zone for nearly 20 feet. The dyke resumes its former width and strike on the opposite side of

the shear zone. The dyke in the vicinity of the shear zone is not sheared. Flow lines are developed in the dyke where the first section described abuts against the shear zone. These indicate that the magma flowed in the dyke, turned 90 degrees, and followed the shear zone in the direction indicated by the dyke veinlet. A similar method of intrusion would serve to explain why the segments of peridotite are offset. In another occurrence, a dyke occupies a sheared portion of a pegmatite dyke. The basic dyke is massive throughout with no evidence of shearing. Examples similar to the two just described were found. This is evidence that the location of the basic dykes was controlled, in part, by pre-existing structures in the gneiss. This makes more plausible the suggestion that the peridotite dyke segments, too, are localized, in part, by structures previously existing in the gneiss.

POST-DYKE DEFORMATION

There is evidence that minor movement occurred in the area after the emplacement of the dykes. In several places, small fault zones, striking easterly, were found in the peridotite. In these places, the peridotite has been altered to talc. Shearing effects are visible up to 10 feet from the fault zone but are usually less extensive. Small faults cutting gabbroic dykes are also present. These are sometimes accompanied by shear zones that contort the whole dyke.

These occurrences are rare and the peridotite outcrops and basic dykes are generally unaffected by deformation.

The country rocks show that the Cuthbert Lake area has been subjected to a high degree of metamorphism. Extensive shearing has also taken place in some locations. But the high degree of freshness and the general lack of disturbance of the peridotite and the associated dyke swarm make it obvious that these rocks were intruded after the waning of the metamorphic and dynamic forces which affected the whole area. Only the final stage of regional metamorphism or a second minor period of movement has affected the basic and ultrabasic dykes.

PETROGRAPHY AND PETROGENESIS

DESCRIPTION OF THE CUTHBERT LAKE PERIDOTITE COMPLEX

Mineralogy and Mineral Associations

Introduction

The composition of the Cuthbert Lake peridotite complex is not uniform. For the purpose of classification, three divisions have been established. The divisions are based on the relative proportions of olivine and plagioclase present in the thin sections.

A "peridotite" is an igneous rock which contains more

than 10 per cent olivine and less than 10 per cent plagioclase, with the remainder made up almost exclusively of pyroxene. An "olivine gabbro" contains more than 10 per cent olivine and more than 10 per cent plagioclase, with amphibole and pyroxene comprising the remainder. A "pyroxinite" contains less than 10 per cent olivine and less than 10 per cent plagioclase, the balance being pyroxene and amphibole formed secondarily after pyroxene. The value of 10 per cent taken as the dividing line between rock types has no particular significance. It is merely a convenient value upon which to base distinctions.

On correlating the Cuthbert Lake ultrabasic rocks to those of Johannsen's classification (1938), it was found that most of the Cuthbert Lake rocks are lherzolites and wehrlites. Minor amounts of cortlandite and saxonite are also present in this group.

All phases of the peridotite complex are composed of olivine, orthopyroxene, clinopyroxene, hornblende, plagioclase, and minor accessories. All these minerals are present in most of the 43 thin sections of the complex which were examined.

In most thin sections, the quantity of pyroxene exceeds that of olivine, though in some sections, this condition is reversed. All the sections show that olivine was the first mineral to crystallize. It was followed by minor primary magnetite and perhaps a spinel. The next mineral group to

form was the pyroxenes. In most of the thin sections, orthopyroxenes had crystallized before clinopyroxene. In some sections, this condition was reversed, and in others these two minerals formed contemporaneously. Plagioclase and hornblende crystallized last. The paragenetic relations of these two minerals resemble those of the pyroxenes.

Major Primary Minerals

Olivine

Several types of olivine occur in the Cuthbert Lake peridotite complex. One prominent form is that of euhedral crystals elongated in the [C] direction. These grains have well-developed pyramidal faces at either end. They occur as individuals disseminated throughout the sections. They sometimes exhibit a preferred orientation, but this is never pronounced. In some sections, these grains show partial alteration to serpentine, but usually alteration is restricted to grain margins or to minute fractures in the grains. The euhedral, elongated grains are often darker than other grains of olivine. This colouration is perhaps due to a high content of iron or to small inclusions of magnetite grains in the crystals. Grains of this type are best developed where olivine in the specimen is under 20 per cent.

Olivine also occurs as small rounded grains. These are indicative of partial resorbtion of the olivine during the process of crystallization. Alteration of these grains

to serpentine is usually complete.

Between these two extremes, all gradations in crystal shape and degree of alteration are found. Most grains are subhedral, with some cleavage faces present. Euhedral and anhedral grains are also common. Another gradation in the olivine is the clarity of the individual grains. Some grains, as mentioned previously, are dark coloured; whereas others are clear, with the typical greenish colour of olivine.

In some thin sections, there are what appear to be two generations of olivine. One is the normal, well-crystallized, medium-grained type that is commonly dark coloured. The other generation occurs as fine-grained subhedral and anhedral fragments. The well-formed grains show no evidence of crushing. The writer concludes that the small fragments represent individual grains which have formed during a period of rapid crystallization. The smaller grains are commonly enclosed in later euhedral pyroxene crystals and are usually not altered.

In one section, olivine exists as separate fragments surrounded by late plagioclase, with the fragments all possessing a similar optical orientation. No evidence of crystal granulation was seen elsewhere in the section, and it is deduced that the fragments are small protrusions from one grain.

In a few sections, olivine forms loosely packed clusters composed of several individual, euhedral grains.

It appears that the grains formed separately, becoming clustered while the rest of the rock was still liquid.

The size of the individual grains of olivine varies. The variation is not from section to section but is usually appreciable within each individual section. The longest olivine grain measured is 2.5 millimeters long. Other grains are 0.1 millimeters long; and fragments of olivine are much smaller. The average variation in a thin section is from 0.75 to 0.25 millimeters. The average size of olivine grains is approximately 0.5 millimeters. Generally, there are more large grains of olivine in a thin section when the percentage of olivine in the section is relatively low. Large grains, usually dark-coloured, are more common in the border phases of the peridotite complex.

Orthopyroxene

Orthopyroxene is rather prominent in the thin sections. Hypersthene is the primary orthopyroxene although enstatite was found in one section. The optic sign was used as a basis for distinguishing these two minerals. In any section in which doubt existed as to which orthopyroxene was present, enough favourably oriented grains were found in which the optic sign could be obtained. Pleochroism of the hypersthene aided in distinguishing this mineral.

Hypersthene is present in many different forms. One prominent form is that of subhedral to euhedral grains. In

this form, hypersthene is usually the second mineral to crystallize. Inclusions of olivine in the hypersthene are common. In some thin sections, the grains are elongated, with a preferred orientation. This is not as apparent as in the olivine grains.

In any one thin section, the grain size and the form of hypersthene are relatively constant. However, variations do exist. One section was found to contain large euhedral grains of hypersthene as well as small subhedral to anhedral fragments of the same mineral. No evidence of mineral granulation was seen in the section; this is presumably the reflection of a period of unstable cooling conditions within the rock.

Hypersthene crystallized after clinopyroxene in some rocks. Thin sections of these specimens show hypersthene in the form of large anhedral grains poikilitically enclosing earlier clinopyroxene and olivine. Occurrences of this type are not common. In many slides, the crystallization of hypersthene and clinopyroxene appears to have taken place contemporaneously.

One phase of the peridotite complex seen in the field was composed of grains of hypersthene up to an inch long. In this form, hypersthene is usually subhedral but good cleavage is commonly developed in the grains. Invariably, the hypersthene contains olivine that is usually well formed. Hypersthene appears to be a product of crystallization "in

situ", as no evidence of granulation can be seen on the outcrops or in the thin sections.

Individual grains of hypersthene appear uniform throughout. However, evidence of zoning is present in some sections. This takes the form of uneven extinction across the grain and is probably a compositional effect, as no indication of strain is exhibited elsewhere in the sections containing these grains.

In several sections, hypersthene contains minute inclusions of another pyroxene. No positive identification of this pyroxene was possible because of its small size. The inclusions possess a higher birefringence and a slightly lower index than the enclosing hypersthene. Poldervaart (1947) discussed occurrences in which lamellae of orthopyroxene are found in a parent orthopyroxene, the two forms having the same composition, but possessing a different optical orientation. Hess (1941) stated that this is an exsolution phenomenon and is due to a calcium-rich clinopyroxene which has exsolved from the orthopyroxene upon cooling. The writer is of the opinion that the examples found in the Cuthbert Lake peridotite complex are lamellae of clinopyroxene in orthopyroxene. This is suggested by the fact that the birefringence of the lamellae is low second-order in some sections.

Clinopyroxene

A clinopyroxene is present in most thin sections. In some sections, it is the only pyroxene present; in others, hypersthene is the only pyroxene. The clinopyroxene is of two types: augite and diopside. The distinction between these types is based on the relation between the vibration direction and the cleavage (Rogers and Kerr, 1942). The reliability of this method in distinguishing between these pyroxenes is questionable. However, the grains identified as diopside were usually of a slightly paler colour than those identified as augite. Also, the grain outlines were best developed in the diopside.

In most thin sections both pyroxenes were identified, with diopside usually slightly more abundant than augite. The order of crystallization of these two pyroxenes is difficult to establish. Generally, diopside forms more euhedral grains than augite, which suggests crystallization prior to that of the augite.

Clinopyroxene formed after orthopyroxene in most sections, although the reverse relationship is sometimes evident. Clinopyroxene commonly encloses earlier formed minerals.

In some examples, clinopyroxene had reacted with olivine during crystallization. In these examples, pyroxene partially surrounds olivine. The outlines of the olivine

are partially rounded adjacent to the pyroxene. At the junction between the two minerals, there is often a thin line of magnetite dust. It appears that the clinopyroxene was unable to incorporate all the iron of the olivine into its structure. The excess iron was converted to magnetite and remains as evidence of the reaction.

In some sections, an inexplicable intergrowth was observed in the clinopyroxenes. This is restricted to particular grains in the section. A single grain is sometimes composed of what appears to be a very fine vermicular intergrowth between clinopyroxenes. Although no evidence of this intergrowth was seen in plain light, it was striking under crossed nicols. There appears to be no definite orientation of the component parts. The lamellae are usually continuous over the length of the grain but are rather irregular. Cleavage is absent in these grains.

Plagioclase

Plagioclase was recognized in all but one of the thin sections of the peridotite complex. The quantity present is variable, ranging from less than 1 per cent to approximately 45 per cent. Despite this extreme range, the composition remains relatively constant. Plagioclase was seen ranging from An_{72} to An_{41}. However, most of the thin sections contain plagioclase between An_{65} and An_{70}.

The composition of the plagioclase was determined by the extinction angle on the albite and carlsbad twins. Although the average percentage of plagioclase in the sections is between 10 and 15 per cent, grains are commonly very well twinned. As a result, the composition of plagioclase in any one section was found after the extinction angle had been measured on an average of 10 grains per slide. The writer feels that the consistency in the composition from slide to slide, as derived by this method, indicates that the method is reasonably accurate.

There is no correlation between the amount of plagioclase present in the slide and its composition. Some of the lowest anorthite values of plagioclase are in sections containing less than 10 per cent of the mineral.

Plagioclase and hornblende were the last minerals to crystallize in the rocks, and, like the pyroxenes, their order of crystallization is interchangeable. Because of this phenomenon, plagioclase is present in several different forms. In places, plagioclase forms separate, subhedral grains. An example of this is presented in Plate I. This type of occurrence is most common when plagioclase crystallizes before hornblende and there is a large percentage of hornblende in the section. However, clusters of subhedral plagioclase were seen in some sections where it has crystallized last and forms a large portion of the groundmass. Plate IV shows plagioclase forming the matrix of the section

although clusters of the mineral are absent. As is evident in the photomicrograph, plagioclase forms large, well-twinned grains which poikilitically enclose the previously formed ferromagnesian minerals. There is no evidence of reaction between plagioclase and these minerals. In most sections plagioclase is anhedral. It occurs in small patches completely interstitial to the earlier minerals, as illustrated in Plate III.

Plagioclase is found in late pegmatitic phases in the peridotite complex. The pegmatites are small lenticular bodies usually no longer than 2 feet. These are not common, but several were seen in outcrops of the peridotite complex. Plagioclase in the lenticles is coarse grained, with crystals attaining a length of 1 inch in places. Crystals are usually subhedral with well developed cleavage. In one section of pegmatitic material, the plagioclase (An_{70}) is relatively fresh and is corroded only around the edges and along fractures in the grains.

In only one section of the complex do the plagioclases show signs of alteration. In this specimen, plagioclase is interstitial and has been reduced to a very fine-grained mass composed of some calcite, a fine-grained clay mineral, and probably quartz plus a more sodic-rich plagioclase. The last two products are too fine grained for positive identification.

Plagioclase is clear in most of the sections, although in some sections it has a brown, dusty appearance

due to the presence of minute unidentified inclusions. It is probable that the inclusions are small magnetite grains.

Amphibole

This mineral is present as both primary and secondary grains in the thin sections of peridotite complex. Both of these types are varieties of hornblende. Hornblende is most commonly associated with plagioclase, and has crystallized after plagioclase in most cases. Sections were seen, however, in which amphibole is the only interstitial mineral present.

In sections with a low hornblende content, this mineral is interstitial. Some degree of reaction is usually present when the mineral is in contact with a clinopyroxene. Reaction rims are not as common when it is in contact with orthopyroxene or olivine.

The primary hornblende varies in colour from green to reddish brown with variations between these colours in some individual grains. Pleochroism is usually pronounced. The cause of the colour variation is not known, as it is not related to reaction with adjacent minerals. Iron or titania might possibly be responsible for this variation in colour. If so, its distribution in the grains is fortuitous.

In some sections, hornblende forms large anhedral grains and constitutes the matrix of the slide. In this form, it encloses the earlier minerals poikilitically

(see Plate I). Good cleavage is present in some of these grains.

Primary Accessory Minerals

Magnetite

Primary magnetite is present in the thin sections. It takes the form of small octahedral or subhedral grains. None is found incorporated in olivine or hypersthene. However, clinopyroxene often contains most of the magnetite. It is also found in hornblende and rarely with plagioclase. Primary magnetite never forms more than 1 per cent of any thin section of the peridotite complex.

Spinel

A spinel is present in some of the thin sections. It is difficult to identify, as grains of the mineral are small. It never forms more than a trace mineral in the sections. It occurs, like magnetite, as small octahedra and as small aggregates. Like magnetite, none is evident enclosed in olivine or hypersthene. It appears opaque in thin section, but the grain margins are slightly translucent and of a brown colour. The spinel is probably chromiferous and a variety of picotite or chromite.

Sulphides

Sulphides were rarely seen in the thin sections of

the peridotite complex. When present, they are only a trace mineral. The grains are individual and minute. The sulphide grains were all identified as pyrrhotite.

Alteration Products

Serpentine

In thin section, serpentine is primarily associated with olivine. In every section, olivine shows some degree of serpentinization. Alteration is usually confined to grain boundaries and fractures within individual grains, but in some sections, olivine is completely altered. Examples of the partially altered grains are included in the plates accompanying this report. Serpentine also partially or completely replaces orthopyroxene in some sections.

Serpentine is present as three species which are identified as antigorite, serpophite, and iddingsite. Antigorite is a flaky serpentine with low first-order birefringence. Serpophite is distinguished from it by its very low birefringence and its amorphous structure. These two varieties are the most common, and the alteration of olivine usually includes them both. Iddingsite is present in some sections in the form of thin alteration rims around olivine grains. This species is brown coloured, with a lamellar structure. The lamellae are perpendicular to the grain boundaries. It was identified on the basis of its colour and its parallel extinction on the lamellae.

In some outcrops, serpentine is intimately associated with the joints. One outcrop has veinlets of serpentine up to 1½ inches wide along the longitudinal joints. Veinlets like this are rare; the average width of the veinlets is approximately 1/8 inch. Serpentine is developed along both tensional joints and longitudinal joints. Although serpentine predominated in one of these two sets of joints on a single outcrop, the preferred joint system varied from outcrop to outcrop. Generally, serpentine is better developed along tensional joints than along the longitudinal joints.

Associated with the serpentine are small stringers of magnetite. When serpentine is found with the longitudinal joints, magnetite stringers are commonly found within the serpentine. However, when the serpentine is concentrated in the tension joints, magnetite lenticles are predominantly developed in small longitudinal joints abutting against the tension joints. Magnetite, in these occurrences, commonly cuts the serpentine and never extends more than a foot from the tension joint.

It is possible that this alteration formed at a late magmatic stage of the dyke injection, after the dyke had partially cooled and the joints had formed. The serpentine is a result of volatiles which attacked the olivine and pyroxene of the dyke, leaving the magnetite as the residual product. Tension joints are thought to be the first joints formed in an igneous body. This accounts for the tendency

of serpentine to form along these joints, as they form the first channels for the migration and concentration of the volatiles from the rock mass. The distribution of magnetite is perhaps due to the fact that the serpentine close to the tension joints could migrate to these joints when they formed and the magnetite could not. This suggests that magnetite has a tendency to remain where it has formed, whereas the serpentine can move to an area of lower stress.

Magnetite

Secondary magnetite is formed when olivine is altered to serpentine. Where iddingsite is the alteration product, magnetite is not formed and the iron is absorbed into the structure of the serpentine. The secondary magnetite forms very fine-grained particles, dust-like in appearance. Its form and association make it readily distinguishable from primary magnetite.

Amphibole

A secondary variety of amphibole, believed to be an aluminous hornblende because of its light green colour and weak pleochroism, is present in many of the sections. It forms narrow rims around the primary minerals, most commonly affecting primary hornblende and clinopyroxene. The alteration also penetrates in cleavage directions in these minerals. In some sections, complete pseudomorphs of horn-

blende after clinopyroxene were found. Orthopyroxene is commonly rimmed with hornblende but the alteration does not proceed past this stage.

A dark, iron-rich amphibole believed to be a variety of hornblende is found rimming some olivine grains. This has much the same appearance as iddingsite but the lamellae have inclined, instead of parallel, extinction.

Uralite is present in the pegmatitic stage of the peridotite complex. In the only section of this phase examined, most of the clinopyroxene had been replaced by the uralite. Plagioclase in this section was also corroded by uralite.

The writer believes the secondary amphibole in the complex to have formed at a late magmatic stage of crystallization.

Talc

Talc, although present in many sections, is not an abundant mineral. It commonly replaces serpentine formed from the alteration of olivine and pyroxene. It also replaces primary hornblende in some sections. Talc has a peculiar green colour and a micaceous habit. These features, plus its high birefringence make it distinctive. In these forms, talc is considered to be the result of late magmatic alterations.

Peridotite is commonly reduced to talc along small

shear zones. Talc in the shear zones has resulted from dynamic metamorphism and is not a late magmatic alteration.

Chlorite

Chlorite is a minor alteration product which generally replaces primary hornblende and clinopyroxene. The chlorite commonly has a greenish brown tinge in polarized light. It, also, is a result of late magmatic alteration.

Banding in the Peridotite Complex

Description of Banding

The outcrops of the Cuthbert Lake peridotite complex are not all alike. Differences in overall mineralogy exist between outcrops as well as within single outcrops. These differences are readily visible in the field.

Several phases of peridotitic rock were recognized. One phase consists of large grains of pyroxene and some olivine. The pyroxene varies in size. In some places it is composed of large individual grains of hypersthene up to 1 inch long. In others each "grain" is composed of a cluster of smaller augite grains. This phase invariably has dark, euhedral grains of olivine enclosed in the pyroxene. Plagioclase is rare and is sporadically distributed. Hornblende is present in places. It occurs as large primary grains, to the exclusion of pyroxene in a few examples. It is also present as a minor, interstitial mineral in some sections.

between the peridotitic complex and the gneiss on both sides of the dyke segments. As previously mentioned, no contacts were found between the segments and gneiss; but in places where exposures are found to within 20 feet of the contact, the pyroxenitic phase of peridotitic rock is the phase that is present.

In one outcrop, six different phases are recognizable on the weathered surface. Contacts are both sharp and gradational between these phases. Thin sections of the first five of the phases were studied. A visual estimate of the mineral percentages in each section is presented in Table II.

TABLE II

Visual Estimate of Mineral Content
in Varying Portions of One Outcrop of Peridotite

Section	Olivine	Hypersthene	Clinopyroxene	Plagioclase	Others
M-637-1-58$	10%	20%	10%	none	Hornblende-60% Magnetite-1
M-637-2-58$	25	10	30	An_{69}-trace	Hornblende-30
M-637-3-58$	15	10	35	An_{62}-10%	Hornblende-30
M-637-4-58$	20	15	50	An_{70}-10	Magnetite-5
M-637-5-58$	15	8	57	An_{60}-15	Hornblende-5

M-637-1-58$ Obtained at the edge of a peridotite outcrop, approximately 15 feet from gneiss.
M-637-2-58$ Taken 43 feet across strike from M-637-1-58$.
M-637-3-58$ Taken 67 feet across strike from M-637-1-58$.
M-637-4-58$ Taken 104 feet across strike from M-637-1-58$.
M-637-5-58$ Taken 121 feet across strike from M-637-1-58$.

Total width of outcrop approximately 140 feet.

The figures in Table II are only approximate. However, a sufficient difference exists to indicate the amount of variation from one phase to another.

Clots of one phase of the complex were found enclosed in a different phase. All the clots found have an elongation roughly parallel to the longitudinal joints in the outcrop. Several outcrops were seen which contain clots of coarse-grained pyroxenite in a finer-grained feldspathic phase. Contacts between clots and the enclosing rock vary from sharp to gradational over 3 or 4 inches. Some clots are 6 feet long and 3 feet wide. Very few are any larger. One outcrop of peridotitic rock was seen which enclosed a clot of very fine-grained material 7 feet by 2 feet. A visual mineral approximation made from thin sections of these types appears in Table III.

TABLE III

Visual Mineral Estimation
for Peridotite "Clot" and the Enclosing Peridotite

Sample	Olivine	Hypersthene	Clinopyroxene	Plagioclase	Others
M-457 (host)	35%	10%	10%	An_{65}-10%	Hornblende-35%
M-457 (clot)	30	25	20	20	Opaques-2%

The strike of the contacts between phases is roughly parallel to the strike of the longitudinal joints in the outcrop in which they occur. However, dips of contacts are

difficult to obtain. No accurate attitudes were found, but bands are most probably dipping steeply to vertical.

Causes of Banding

Vertical banding in igneous rocks has been described in the literature. Coats (1936) reported small scale, vertical banding in a volcanic plug in the Monteregion Hills. He stated that the banding is due to the alternation of mineralogically unlike layers, already differentiated before the magma reached its present position. Coats stated that bands may have any attitude but they are commonly parallel to the contact of the intrusive body. He also reported that the thickness of bands varies up to many feet and that contacts between bands may be gradational or sharp.

Harker (1904) described banding in the peridotite rocks of Skye. He believed that large-scale banding is due, in part, to distinct injections. There is no evidence of the transgression of bands. Harker stated that the absence of a chill phase between two bands is evidence that the earlier phase was still fluid when the later one was forced in.

Judd (1893) described banded dykes in Arran. He postulated that differentiation of a magma had taken place in a subterranean chamber. Successive injections of different fractions of the magma along the same fissure then gave rise to the banded dykes. Judd also reported that later injections are most commonly found to intrude the centre of earlier

injections. This occurs because of the fact that the interior of the earlier injection is the last part to solidify. It is, then, a zone of weakness until it cools to a solid. As such, it is the channel for a fresh pulsation of magma.

The writer believes that the bands in the peridotite complex at Cuthbert Lake must have originated in a similar manner to those described by Judd. The peridotite complex has been shown previously to be a dyke relatively undisturbed by folding or metamorphism. Therefore, near-vertical banding precludes the theory that the bands originated from differentiation "in situ". Also, the composition of the various bands shows no progressive order of crystallization with the continual enrichment in later bands of later minerals. This is further evidence that differentiation did not take place "in situ". Contacts between phases of the complex are undulatory but are not transgressive. As mentioned previously, they are either sharp or gradational. For such contacts to exist, different periods of injection must have taken place. The presence of xenoliths of the early pyroxenitic phase in later phases of peridotitic rock further substantiates this supposition.

From the nature of the contacts within the peridotite complex, it appears that earlier phases had not completely cooled before other injections of magma occurred. This is indicated by the absence of chilled contacts even where

contacts are sharp. The presence of the pyroxenitic phase on both borders of the dyke segments indicates that this phase was the first to be intruded and that the rest of the complex was injected later. In some cases, it is doubtful that some phases had completely crystallized before another injection of magma took place. This is indicated by the presence of gradational contacts between distinctly different phases.

The texture of the thin sections of the peridotitic rocks indicates that the rocks were intruded in primarily a liquid state. In none of the sections is there evidence of either crystal granulation or recrystallization of the constituent minerals, which must be present if the material was intruded as a crystalline mush. On the contrary, the hypidiomorphic-granular texture of the sections indicates normal crystallization of the minerals "in situ".

However, the writer does believe that there was a partial crystallization of some of the minerals before intrusion into their present position. This is suggested by the large, well-shaped crystals of olivine and hypersthene. Although this might be expected from normal crystallization "in situ", the preferred orientation shown by these grains in some sections shows that they must have formed before the injected magma had come to rest. This is clearly evident in Plate VII. The photomicrograph is of a contact between paragneiss and an ultrabasic dyke 25 feet in width. The

matrix of the dyke material looks like recrystallized glass; its constituents are too small to identify. However, large olivine grains present in this material show a preferred orientation parallel to the contact. This shows that this dyke material was a liquid containing some crystals in suspension at the time of injection. The presence of similar olivine grains in well-crystallized dyke segments indicates that these grains have had a similar history.

The size of crystals of olivine and hypersthene compared to other minerals in the same section indicates that the olivine, and, in some specimens, hypersthene, had formed before injection. The presence of two phases of these minerals in some sections suggests that there was a rapid temperature change early in the crystallization history. In some sections previously described, olivine occurs as large euhedral grains and as minute anhedral grains. Hypersthene occurs in the same manner in some sections. This suggests that the larger grains formed slowly at depth. Before crystallization was complete, the liquid was forced into cooler surroundings. At these lower temperatures, the remainder of the olivine crystallized rapidly in the form of the small grains observed. A parallel cooling history is probably responsible for the two generations of hypersthene found in some sections.

The composition of the liquid from which the dyke material crystallized is not known. However, an analysis of

olivine-free dyke material from the contact just described should give a reasonable approximation of the composition. This was not done by the writer. That the liquid magma was quite basic is indicated by the mineralogy of the rock. From the nature of this contact, the magma does not appear to have been excessively hydrous. An above-normal quantity of amphibole is developed in the gneiss up to 1½ inches from the contact. The crystallization of primary hornblende, the presence of coarse-grained pegmatitic phases and the development of late magmatic, hydrous, secondary minerals all indicate the presence of some water vapor. But the degree of freshness of the pyroxenes and olivines in the sections indicates that the content of volatiles was very low in the original magma.

Metamorphic Effects of the Peridotite Complex

Contacts between peridotitic rock and the enclosing gneiss are rarely exposed. Therefore, the metamorphic effects of the complex are difficult to ascertain. However, the writer was able to obtain the following information in the area.

North of Buckingham Lake along the creek draining Begg Lake, an outcrop of paragneiss was found with a layer 6 inches wide of chilled dyke material along one side. As the dyke material was adjacent to the lineament caused by the erosion of peridotite, it was thought that the chilled

phase might represent the border of a peridotitic dyke segment. Three thin sections of the gneiss were studied in order to ascertain the effects of the dyke on the rock. One section was taken from the contact; the second, 1 foot from the contact; the third, 12 feet from the contact. Except for alteration of hypersthene, no change which could be caused by thermal metamorphism is present in the specimens. In the contact sample, only remnants of hypersthene are present in the slide; it is almost completely altered to actinolite plus some anthophyllite. At 1 foot from the contact hypersthene forms large grains which have reaction rims of a light green amphibole, probably actinolite, surrounding them. It is probable that this change is due to the thermal effects of the dyke which initiated retrogressive metamorphism. No evidence of hypersthene or possible alteration products was found in the remaining section.

At the north end of Cuthbert Lake, a contact is exposed between a 25-foot wide peridotite dyke and the enclosing gneiss. Samples of gneiss were taken at the contact, 15 inches from the contact, and 10 feet 10 inches from the contact. No progressive change in the mineralogy and texture of the gneiss is evident in sections of these samples. The only abnormality is a pronounced development of dark, iron-rich amphibole and biotite in the gneiss up to 1 inch from the contact.

Benson (1918) described occurrences of ultrabasic rocks in which soda has been expelled. To determine whether alkali metasomatism had accompanied the intrusion of peridotite, the writer analyzed samples of the three specimens for sodium and potassium, using a flame photometer. The results are as follows.

TABLE IV

Analyses of Alkalies in Gneiss
Adjacent to Peridotite - Cuthbert Lake

Sample	Distance from Contact	% Na	% K
P-596-B.	.0 inches.	6.22.	3.99
P-596-C.	.15 inches	6.39.	2.67
P-596-D.	.130 inches.	6.21.	2.65

This analysis suggests that potassium from the country rock has been mobilized and concentrated along the contact of the peridotite complex. The low content of potassium in the peridotite as shown in the following analyses makes it improbable that it has been expelled from the peridotite. The high content of potassium in the contact sample is probably incorporated in the excess of biotite and hornblende found in this section. There is no indication from the analyses that sodium has migrated at all.

The small peridotite dyke also contains an inclusion of gabbroic rock. In a thin section of this inclusion,

plagioclase shows some alteration to epidote. Both clinopyroxene and orthopyroxene are either partially or completely uralitized.

From the study of the above specimens, it appears that the temperature at which the complex was intruded was at least equivalent to the upper range of the epidote-amphibolite facies. Also, if the country rock adjacent to the complex reached the same temperature as the peridotite melt itself, then the temperature of intrusion of the 25-foot-wide dyke did not extend into the temperature conditions of the pyroxene-granulite facies. This places the minimum temperature of the intrusion of the dyke between 400°C. and 500°C. Thermal equilibrium between the dyke and the enclosing gneiss or the inclusion could not have been reached as unaltered olivine and pyroxene are still present in the dyke. If equilibrium had been attained, then pyroxene should show alteration to hornblende. Therefore the minimum temperature values for intrusion are probably too low. No similar studies were possible with the peridotitic rock which forms the individual dyke segments.

Alteration of the primary minerals of the peridotite complex has been discussed previously. Apart from this alteration, several locations were found in which dynamic metamorphism, in the form of small shear zones, had affected the peridotitic rock. A section of one shear zone revealed that no primary minerals remain. The ferromagnesian minerals

have all been reduced to tremolite, anthophyllite, and chlorite. Plagioclase has recrystallized and much calcite and some epidote are present. The oxide minerals are limonite and hematite. In other shear zones, talc is the predominating mineral.

DESCRIPTION OF THE ASSOCIATED BASIC DYKES

Several thin sections of the basic dykes associated with the peridotite complex were examined. The mineralogy of the dykes is essentially the same as that of the complex. In some sections, some minerals characteristic of the complex are absent. The most distinctive difference between the sections of basic and peridotite dykes is in proportions of the constituent minerals and the change in texture resulting from this.

The most prominent change between the ultrabasic complex and the basic dykes is in the plagioclase. The sections of basic dykes which were examined contain an average of 45 per cent of this mineral and 60 per cent is not uncommon. Also, plagioclase is commonly present as individual grains. It is not a late interstitial mineral, but is one of the first minerals to crystallize. The grains are lath-shaped in some dykes, giving the rock a diabasic texture. In the basic dykes plagioclase ranges from a medium andesine to a sodic labradorite, whereas in the peridotite complex the range is from calcic labradorite to

sodic bytownite. Plagioclase is not uncommonly zoned in the basic dykes and the zones are always more calcic towards the centre of the grains. Zoned plagioclase is not present in the peridotitic rocks. The plagioclase is also much more "dusty", due to minute inclusions, in the basic dykes than in the complex.

Olivine and hypersthene are rare in the basic dykes. Many of the sections of the basic dykes contain neither of these minerals. However, in some they are present as trace minerals and in others form a total of 15 per cent of the section. These minerals, when present, are euhedral, but always show partial or complete alteration to amphibole or serpentine.

Clinopyroxene is always present in the basic dykes. Some outcrops are characterized by numerous phenocrysts up to $\frac{1}{2}$ inch long. In thin section these phenocrysts are euhedral to subhedral but often completely or partially altered to uralitic amphibole. This alteration is much more common in the basic dykes than in the peridotite dykes. Clinopyroxene is either the first or the second mineral to form in the basic dykes. It alternates with plagioclase in this respect.

Some minerals are found in the basic dykes which are absent from the peridotite complex. These are quartz, apatite, and biotite. The latter two minerals are only accessories in the sections examined, but quartz forms up to

10 per cent of some sections. All these minerals are primary.

Amphibole is present in the basic dykes as both a primary and secondary mineral. Secondary amphibole is mostly uralite, associated with the clinopyroxene as mentioned previously. A second variety is found as rims around the pseudomorphs of uralite in some sections. Primary amphibole, believed by the writer to be hornblende, generally has a definite brownish tinge in the basic dykes. However, this colour is solid and not unevenly distributed as it is in grains of hornblende found in the peridotite complex.

Titanium is thought by the writer to be more common in the basic dykes than in the ultrabasic complex. The clinopyroxenes in some sections of the basic dykes have a purplish tinge indicative of the presence of titania. This feature is not evident in the peridotitic rocks. Also, sphene is present in the basic dykes. It is found in conjunction with the alteration of primary hornblende to secondary amphibole. In this reaction, titanium appears to have been released from the primary grains with the ensuing formation of sphene. Sphene is never encountered in the peridotitic rocks. Titaniferous magnetite or ilmenite is also present in the basic dykes. Formation of leucoxene on some of the opaque minerals is proof of this. Leucoxene was not observed in the sections of the peridotite complex.

Some basic dykes have visible sulphides disseminated through them. Sulphides identified in the dykes are pyrite, chalcopyrite, and pyrrhotite. The sulphides are, however, present as only a trace mineral in the thin sections. In three locations, trenches are present in the basic dyke where small showings of sulphides occur. One showing has had several feet of core drilled from it. None of the showings appear to be of any economic significance.

DESCRIPTION OF THE OLIVINE DIABASE DYKES

The writer found very little evidence of the presence of olivine diabase dykes in the area. One outcrop was found that contained small dykes striking north 70 degrees west, cutting gabbro dykes with the typical northerly strike. A thin section indicates that the younger dyke contains a higher percentage of magnetite than any of the basic dykes. The minerals also have a very fresh appearance in thin section, in contrast to the altered nature of the ferromagnesian minerals of the basic dykes. Dr. H. D. B. Wilson (personal communication) describes olivine diabase dykes in the vicinity of Ospwagan Lake. The dykes in this area are fresh in appearance and contain a high percentage of magnetite, which accounts for pronounced magnetic anomalies associated with the dykes. The dykes at Ospwagan Lake have the same attitudes as the dyke seen by the writer in the Cuthbert Lake area. Dykes with similar attitudes but which

do not exhibit intrusive relationships with other dykes are present in the Cuthbert Lake area. On the basis of the similarity of the dykes in the two areas, the writer believes that there has been an intrusion of olivine diabase dykes in the map-area. These dykes are later than the basic dykes comprising the dyke swarm and are the last intrusive rocks recognized in the area.

DESCRIPTION OF THE MOAK LAKE SERPENTINITE

Introduction

Little is known about the Moak Lake-type serpentinite. It appears to be localized along a structural break extending from Split Lake to Setting Lake. According to Quinn (1955), the serpentinite along this break is sinuous and lenticular in shape.

The International Nickel Company supplied three sections of samples across the serpentinite body at Moak Lake. The samples are 1-inch to 2-inch pieces of drill core taken approximately every 20 feet across the serpentinite. No information on the attitudes of the drill holes or of the serpentinite body was supplied, so it is not known if the three drill holes represent one composite sample or if they each represent a cross-section of the body. It is not known if the length of each drill hole represents a true width of the serpentinite. However, the samples do represent the

body from hanging wall to footwall (personal communication, G. W. Thrall, Exploration Geologist, Canadian Nickel Company, Limited). Vertical intersections between the drill holes and the serpentinite average 700 feet below surface.

The width of the serpentinite, as represented by the three sets of samples, is 506 feet, 490 feet, and 400 feet. The samples were logged, and thin sections made from representative samples. Polished sections were also made from sections of core that contained visible disseminated sulphides.

Core Specimens

The specimens from the three sections of serpentinite are composed primarily of serpentine with minor quantities of other secondary minerals. Shearing is evident in many of the specimens, but is especially prevalent near the margins of the body. In two sections, the margins are sheared for a distance of 70 feet in from both contacts. In the third section, the shear zone is not as wide. Minor slips are present throughout the sections but these zones are usually less than an inch wide.

The sheared serpentine has a medium to light green colour. Carbonate veinlets are common and hematite stains are present along shear surfaces and as flecks throughout the core. In unsheared portions, the colour changes to dark green, with small light green flecks and specks of red

hematite throughout. Pseudomorphs of primary minerals are obvious on the surface of the core. Small veinlets of serpentine, in some places chrysotile, are present in some specimens. Disseminated sulphides and sulphides along shear zones, though rare, can be seen in the core.

Thin Sections

A study of thin sections shows that no primary minerals remain in the rock. However, distinct pseudomorphs of antigorite and serpophite after olivine are common in unsheared portions. The pseudomorphs usually have an elongated shape and show a strong preferred orientation. An example of this is presented in plate IX. Pseudomorphs of serpentine after pyroxene are also recognizable. The difference between olivine and pyroxene pseudomorphs can, in places, be recognized by the distribution of magnetite formed as a result of the alteration of the primary minerals. From the appearance of the thin sections, this rock was once composed primarily of olivine.

In sheared portions of the serpentinite, no pseudomorphs are recognizable. The antigorite flakes are either destroyed or show a strong orientation suggestive of the fact that serpentinization took place prior to shearing. Carbonate is disseminated throughout most of the sheared portions. In places, actinolite needles are common. Chlorite is also prominent in sheared serpentinite and appears to be an

alteration product of the serpentine.

A chemical analysis of this rock is given in Table V. The analysis was made on a composite sample composed of drill core specimens from hole number 12993, supplied by the International Nickel Company of Canada. Core specimens were taken every 20 feet between 320 and 670 feet inclusive. Specimens in this interval were relatively weakly sheared. Care was taken in eliminating veinlets of secondary material from the sample.

From thin section and polished section study, as well as from examination of the core, no difference was seen between the section analysed and the other sections available.

The chemical analysis obtained from the composite specimen is assumed to represent the composition of the Moak Lake serpentinite and similar ultrabasic bodies in the area.

Polished Sections

Several polished sections were examined from core specimens in which disseminated sulphides were visible. The only sulphide mineral seen was pyrrhotite. It is present in small blebs, as is evident in Plate X. Grains are found within olivine pseudomorphs as well as around the borders of recognizable pseudomorphs.

Although pyrrhotite commonly occurs as separate grains, it is also present associated with magnetite. In this form,

TABLE V

Chemical Analysis of the Moak Lake Serpentinite

SiO_2	36.46%
Al_2O_3	3.00
Fe_2O_3	6.48
FeO	3.65
CaO	0.76
MgO	35.65
Na_2O	0.03
K_2O	0.02
H_2O^+	10.92
H_2O^-	0.28
TiO_2	0.15
P_2O_5	0.05
MnO_2	0.09
CO_2	0.80
S	0.50
NiO	0.91
Cr_2O_3	0.44
Total	100.23
Less $\equiv$S	0.19
Total	100.04

Analysed by S. Courville, Analytical Chemical Division, Geological Survey of Canada.

the two minerals form a single grain with an irregular contact present between the two minerals. It is possible that the pyrrhotite has formed from the alteration of magnetite. Most of the magnetite in the sections, however, has obviously formed from the alteration of olivine, as its close association with pseudomorphs is obvious in some polished sections.

ORIGIN OF THE BASIC AND ULTRABASIC DYKES OF THE CUTHBERT LAKE DYKE SWARM

Introduction

The basic and ultrabasic dykes of the Cuthbert Lake area form a major part of the lithology of the area. Both the similarities and differences of these dykes indicate that they are genetically related. The writer has put forth the suggestion that bands of the peridotite complex of varying composition were caused by the injection of chemically different magma portions from the same source. Proceeding with this theory, it is the writer's belief that the basic and ultrabasic dykes represent different portions of an igneous mass that differentiated at depth. The remainder of this section will be devoted to the study of the relationship between the ultrabasic and basic dykes.

Petrology

The petrology of the ultrabasic and basic dykes suggests that these igneous bodies were derived from the same magma chamber. Progressive changes in the mineralogy which parallel the changes observed in differentiated lopoliths are present in the dykes.

One similarity common to the ultrabasic and basic dykes under consideration is their mineralogy. The same minerals are found in the dykes of all compositions. However, the ratio of one mineral to another varies as the rock becomes less basic. No mineral is present in one group of rocks and absent in the other, to indicate different origins for the dykes. In addition, the same forms of some minerals are common throughout the sequence. Olivine and hypersthene are examples of this. Olivine is present in two principal forms: as elongated euhedral crystals terminated by pyramidal faces, and as rounded anhedral grains. Both types are present in both the ultrabasic and the basic dykes. Also, euhedral grains of hypersthene of uniform size are included in feldspathic portions of the peridotite complex as well as in the associated basic dykes. Euhedral grains of clinopyroxene are present in some sections of the ultrabasic dykes as well as in the basic dykes. The presence of similar forms of these constituent minerals suggests that the dykes had a common origin.

Variations in the percentages of the minerals present in the dykes indicate that differentiation of the source magma took place prior to the injection of the dykes. Evidence for this is the decreasing ferromagnesian to plagioclase ratio, corresponding to the increasing silica percentage, proceeding from ultrabasic to basic dykes. Samples of peridotitic rocks contain between 100 per cent and 55 per cent ferromagnesian minerals. In the basic dykes, these minerals compose only 35 per cent of some rocks. A complete gradation exists between these extremes.

There is, in addition, a variation in the type of ferromagnesian minerals present. In rocks with a low silica content, olivine forms the bulk of the sample in many cases. As feldspar becomes more prominent, the percentage of olivine decreases, through to the basic rocks. In one basic dyke, 15 per cent olivine is present. Olivine is, however, usually either present as a trace mineral or absent from the basic rocks. The same trend is observed with hypersthene. As this mineral formed after olivine in most cases, it is less plentiful than olivine in most ultrabasic rocks. In the least basic rocks, in which olivine is absent, hypersthene is commonly present in trace amounts. When both minerals occur in the basic rocks, hypersthene is usually predominant over olivine. Clinopyroxene parallels these minerals in that its content also varies with the rock type. However, it is enriched in the basic rocks in comparison to the ultrabasic

rocks. It is a major constituent in the basic rocks and is usually present to the exclusion of the earlier-formed ferromagnesian minerals. These three minerals crystallize in the same order and are enriched in the same phases of the dykes as they are in differentiated lopoliths.

A change is also noted in the composition of the plagioclase in these rocks. In the peridotite rocks, the average range of the plagioclase is between An_{65} and An_{70}. In the basic dykes, this range is An_{45} to An_{50}. A complete overlap in these values exists between the ultrabasic and basic rocks. However, the general trend, shown by the decreasing calcium content of the plagioclase and accompanied by a corresponding increase in silica content of the rock, again is similar to the basaltic-type magma.

The titanium content of the rocks also appears to increase with increasing silica. No evidence for the presence of titanium was noted in the peridotite rocks. However, in the basic dykes, some clinopyroxene had a purplish tinge indicative of the presence of this element. Also, the presence of sphene in conjunction with the alteration of primary hornblende indicates the presence of titanium in the amphibole. Leucoxene associated with the opaque minerals indicates the presence of titaniferous magnetite or ilmenite. Trace element studies show titanium to be enriched in the later ferromagnesian minerals, such as hornblende and biotite. Its concentration in the basic dykes is in accord with the

process of normal differentiation.

Primary magnetite was found to follow the general pattern common to differentiated intrusions. Although present in the peridotitic rocks, it usually forms less than 1 per cent of this rock. In the basic dykes, magnetite commonly forms 3 per cent to 5 per cent of the rock. This parallels its occurrence in lopoliths, in which magnetite is usually concentrated near the contact between noritic and gabbroic phases.

In a differentiated igneous mass, the more basic phases are found to have a lower concentration of volatiles than the more acidic phases. This relationship is evident in the dykes of the Cuthbert Lake area. The peridotite phase shows little evidence of the presence of volatiles. The commonly low percentage of hydrous minerals suggests that water vapor was present in only a small amount. The basic dykes contain a larger percentage of hydrous minerals. The alteration of primary pyroxene to amphibole is common in the basic rocks. This change also appears to be gradational from the ultrabasic to basic rocks, as some of the ultrabasic phases have an appreciable content of hornblende.

There is petrographic evidence that partial crystallization of the magma had been attained before it was injected as dykes. Phenocrysts of olivine in the chilled phases of the peridotitic rocks, and of clinopyroxene and plagioclase in the chilled phases of the basic dykes is the best evidence

for this. It is supported, moreover, by the development of two generations of olivine and hypersthene in some of the specimens of the ultrabasic dyke segments. One generation is coarse grained, forming euhedral crystals which indicate a long period of formation under slowly cooling conditions. The other phase consists of a profusion of minute, anhedral fragments suggestive of rapid cooling. One interpretation of these phenomena is that the large crystals formed in a deep-seated magma chamber. Before crystallization was complete, intrusion of this portion of the magma into a cooler environment took place, resulting in the rapid formation of the remainder of the mineral. In some sections, olivine and hypersthene form euhedral crystals which are much larger than the other constituents. These are found in the ultrabasic as well as the basic dykes, and suggest that these minerals formed under more slowly cooling conditions than did the remainder of the grains.

In this regard, the plates accompanying this report are instructive. Large euhedral grains of olivine, hypersthene, and clinopyroxene are evident. The interstitial character of plagioclase and/or amphibole is also apparent. Plate VII showing the contact between a peridotite dyke segment and the enclosing gneiss provides proof that grains had crystallized from the magma prior to intrusion. Similarly shaped crystals of olivine and hypersthene are present in both the peridotite dyke segment and the basic dykes. This

is further evidence that these dykes had a common origin.

Chemical Composition

The results of two chemical analyses of the rocks comprising the Cuthbert Lake dyke swarm are presented in Table VI.

A microscopic examination of specimen M-667-58 (Table VI) reveals that it is composed of approximately 25 per cent subhedral to euhedral olivine crystals which are present as clusters and as individual grains found throughout the slide. Olivine clusters are evident in Plate II, a photomicrograph of the thin section. No obvious orientation to the olivine is evident. The crystals have a very "dusty" appearance because of small inclusions of magnetite. Talc has formed as an alteration product of olivine and constitutes roughly 5 per cent of the section.

Euhedral hypersthene, forming approximately 20 per cent of the section, encloses olivine and has crystallized later than olivine. Undulatory extinction of individual grains suggests that they are zoned. Grains of hypersthene in this section show no obvious pleochroism but are optically negative, indicative of a high magnesium content.

Clinopyroxene shows evidence of crystallizing later than both olivine and hypersthene, as it forms rims around these minerals. This could be due to a reaction phenomenon between the first formed crystals and the remaining liquid.

TABLE VI

Chemical Analysis of
a Peridotite Rock and a Basic Dyke - Cuthbert Lake

Oxide	(1) M-667-A-58	(2) P-538-58
SiO_2	42.21%	48.76%
Al_2O_3	5.92	14.01
Fe_2O_3	2.96	3.94
FeO	7.25	7.46
CaO	4.68	13.55
MgO	29.07	6.90
Na_2O	0.70	1.68
K_2O	0.21	0.13
H_2O^+	5.06	0.52
H_2O^-	0.20	0.41
TiO_2	0.30	0.57
P_2O_5	0.03	0.06
MnO	0.16	0.15
CO_2	0.15	0.15
S	0.07	0.08
NiO	0.48	trace
Cr_2O_3	0.36	0.16
Total	99.81	N.D.
Less O ≡S	0.03	
Total	99.78	98.53

(1) Peridotite. Analyst: S. Courville, Analytical Chemical Division, Geological Survey of Canada.

(2) Basic Dyke. Analyst: D. Brown, Assay Laboratory, Manitoba Mines Branch.

Euhedral grains of clinopyroxene are present, but are restricted in their development by earlier crystals of olivine and hypersthene. Clinopyroxene forms approximately 30 per cent of the thin section.

The remaining minerals, excluding a trace of primary magnetite, are hornblende and plagioclase, both interstitial. Each constitutes approximately 10 per cent of the thin section. A portion of the hornblende is secondary, forming reaction rims around the pyroxenes and olivine. The majority is primary hornblende, with a typical dark reddish brown colour. The plagioclase is unaltered. Its composition, as determined from extinction angles from the albite twins, is An_{62}.

In Johannsen's classification of ultrabasic rocks (1938), this specimen resembles a lherzalite.

Specimen P-538-58 represents one of the associated basic dykes of the dyke swarm. The relative proportions of the minerals in this section were estimated by traversing the thin section with a mechanical stage. Over sixteen hundred mineral determinations were made.

This thin section contains 5.7 per cent olivine, most of which is altered to serpentine or hornblende. These grains are typically rounded in the basic dykes.

Plagioclase forms 41.7 per cent of the thin section. Its composition, determined by extinction angles on albite twins, is An_{62}. It commonly forms well-shaped lathes which give the rock a good diabasic texture. An example of the

texture formed is presented in Plate VIII. This mineral has apparently crystallized contemporaneously, at least in part, with clinopyroxene. Some small lathes are enclosed in later-formed pyroxene. However, pyroxene appears to have ceased crystallizing before plagioclase stopped forming.

Hypersthene forms 1.2 per cent of the thin section. It forms subhedral to euhedral grains. Some small grains are imbedded in feldspar.

Clinopyroxene, along with plagioclase, constitutes the major portion of the rock. The thin section contains 43.0 per cent of these minerals. Clinopyroxene usually forms subhedral to euhedral grains.

Primary hornblende with narrow rims of secondary hornblende forms 6.6 per cent of the thin section.

Primary magnetite, forming 1.7 per cent of the section, makes up the remainder of the thin section.

In addition to these analyses, two determinations of silica in rocks of the Cuthbert Lake peridotite are presented in Table VII.

TABLE VII

Silica Analyses for Two Cuthbert Lake Peridotite Samples

Sample	SiO_2 %	An content of plagioclase
M-522-C-58	45.34	An_{60}
M-486-58	45.94	An_{68}

Analyst: D. Brown, Assay Laboratory, Man. Mines Branch.
Anorthite content estimated from extinction angles on albite twins.

Structure

The structural analysis of the basic and ultrabasic dykes has been discussed. The features suggesting a possible origin for these dykes will be reviewed briefly in this section.

It was stated previously that the overall strike of the Cuthbert Lake peridotite complex is north 28 degrees east. The predominant strike of the basic dykes on both sides of the peridotite, as derived from Figures 7 and 8, is north 30 degrees east. The difference in the attitudes of these rock types is negligible.

Evidence has been presented indicating that the ultrabasic dyke segments occupy a fracture zone of weakness which was probably activated by tensional forces to allow the intrusion of this rock. Field evidence was also presented indicating that the forces which caused the fractures now occupied by the basic dykes was tensional. There is thus a similarity in the forces initiating the fractures for both types of dykes.

These two features, the similarity in the attitudes of the dykes and the similarity in the proposed forces causing the fractures occupied by the dykes, suggest a common origin of the basic and ultrabasic rocks. The most reasonable source for the rock material is a deep-seated magma chamber.

Summary

Three lines of evidence: petrological, chemical, and

structural, point to a common origin for the basic and ultrabasic dykes in the Cuthbert Lake area. The evidence indicates that this source was a partially differentiated magma and that the differentiation of the magma took place at depth into the phases represented by the dykes of varying composition.

DISTINCTIONS BETWEEN THE MOAK LAKE SERPENTINITE AND THE CUTHBERT LAKE PERIDOTITE COMPLEX

The Moak Lake serpentinite and the Cuthbert Lake peridotite complex are both ultrabasic rocks. However, numerous distinctions can be made between them.

These differences are obvious in a comparison of the petrology of the two rock types. As the petrology for these rocks has been discussed previously, only a list of the differences will be compiled here.

1. The original mineral composition of these two rock types differs. In places where the Moak Lake serpentinite has not been sheared, the original mineral content is discernable from outlines of pseudomorphs. These indicate that the rock was composed primarily of olivine with minor orthopyroxenes and oxides. The Cuthbert Lake peridotite complex has a much more varied mineral content, and grades into basic gabbros in places.

2. A strong orientation is visible in the grains of olivine replaced by serpentine in the Moak Lake body. An

orientation is present but to a much lesser degree in the Cuthbert Lake peridotite rock.

3. The minerals of the Cuthbert Lake peridotite rock are quite fresh, with only minor alteration visible. The Moak Lake serpentinite consists entirely of secondary minerals.

4. The chemical compositions available for these rocks show that the Mg ratio for the Moak Lake serpentinite is 7.68. The Mg ratio for the most ultrabasic rock available from the Cuthbert Lake district is 3.09.

5. The CaO and Al_2O_3 contents for the Cuthbert Lake rocks are much higher than the corresponding values for the Moak Lake serpentinite.

6. The Moak Lake serpentinite and similar rocks have no known associated less basic rocks. The Cuthbert Lake ultrabasic rocks have a large number of basic dykes associated with them.

7. Occurrences of rocks of the Moak Lake-type serpentinite are restricted to a major structural break in the area, and are highly sheared, especially along the borders. In contrast, the Cuthbert Lake dyke swarm occupies an area of considerable areal extent, and shows no evidence of major contemporary deformation.

A comparison of these distinctions with those established by Hess for distinguishing between Alpine-type and Bushveld-type ultrabasic rocks is illuminating. It is readily apparent

that the Moak Lake serpentinite corresponds closely to Alpine-type peridotite; whereas the Cuthbert Lake peridotite closely resembles the Bushveld-type. However, unlike rocks typical of the Bushveld-type peridotite, in which differentiation has taken place "in situ", the rocks of the Cuthbert Lake dyke complex have been differentiated at depth and then intruded.

CHAPTER IV

TECTONICS OF THE THOMPSON LAKE - MOAK LAKE AREA

INTRODUCTION

This chapter will deal with the general tectonic features of the Thompson Lake - Moak Lake area. Special reference will be made to the Moak Lake serpentinite and the Cuthbert Lake dyke swarm.

DISCUSSION

As early as 1910, Sederholm (J. T. Wilson - 1954) recognized that the Archean should be divided into structural provinces, each with a pattern of strike or of foliation peculiar to it. More recently, several authors, among them J. T. Wilson (1949), have attempted to divide the Canadian Shield into structural provinces. As a result of this work, several boundaries between provinces have been advocated. One is the boundary lying between the Superior Province in the southwest part of the Canadian Shield and the Churchill Province in the northwest part of the shield. The boundary between these provinces has been chosen as the Nelson River Valley.

With the recognition of definite structural breaks in the Precambrian shield area of Canada and in other regions of the world, a theory of continental growth by accretion has been suggested, championed in Canada by J. T. Wilson. The proponents of this theory believe that growth of continental areas took place around a central nucleus, with growth marked by a series of concentric orogenic zones. Several areas have been described as having orogenic zones located in this manner. Hess (1937) reported that in Australia, orogenic zones are arranged in a concentric pattern, becoming progressively younger away from the nucleus.

Orogenic zones marking structural breaks are commonly characterized by compressional mountain ranges or their eroded roots. As has been discussed previously, compressional mountain belts are believed to be related to present day island arc systems. It has been advocated by J. T. Wilson (1954) that continental areas grow concentrically by the development of a series of island arc systems along their marginal areas.

Several features of the Thompson Lake-Moak Lake area indicate that it was once part of an active island arc system. These features will be discussed in the paragraphs to follow.

The topographic map of Manitoba reveals the presence of a strong structural break in the central part of the province. This is depicted by the drainage pattern in this area. The line marking the break is represented in the east

by the Nelson River Valley. From here, the line extends westward to Split Lake and Assean Lake, and then along the Burntwood and Odei Rivers to Mystery Lake. At Mystery Lake, the line swings southerly and passes through Ospwagan Lake to Setting Lake. At Setting Lake, the line swings westerly and disappears under the Palaeozoic cover. Water courses to the south of the break have a pronounced northeasterly trend parallel to the break from Mystery Lake to Setting Lake. Those to the north of the break possess a dendritic type drainage pattern. The break can be seen on the gravity map of central Manitoba that accompanies this report.

The presence of this structural trend is readily apparent. However, there are several features which indicate that it marks the position of an old island arc system. One of these is the lithological sequence associated with the feature. In the vicinity of Mystery Lake, greywackes, argillites, quartzites, and iron-formations are exposed. This sedimentary belt extends discontinuously along the break to Split Lake in the east and to Setting Lake in the south. These types of sediments are typical associations of present day island arc systems. In the Cuthbert Lake area, quartzites and limestones, apparently contemporaneous with the paragneiss, indicate that the area was once part of a sedimentary basin. Lavas interbedded with gneisses along the Odei and Burntwood rivers indicate that the area was unstable during the period in which sedimentation was taking place. This association is

also typical of island arc areas.

It has been suggested (Harrison, 1951) that the gneisses of this area might be correlated with the Kisseynew gneisses of the Flin Flon area, as different authors have described the gneisses of these two areas in a similar manner. Harrison stated that the Kisseynew gneisses represent metamorphosed sediments which were deposited in a geosynclinal trough and which underwent mountain building. He stated:

> "If the gneisses mapped as pre-Assean by Dawson to the east, and the gneisses mapped much further west, in Saskatchewan, are part of the Kisseynew, the basin had a length of 250 miles."
> (J. M. Harrison, 1951, p.47)

The metamorphic grade of the paragneiss in the Cuthbert Lake area and in the Thompson Lake-Moak Lake area is the pyroxene granulite facies. Such conditions are attained only during the extremes of regional metamorphism such as might be encountered during an orogenic period. Evidence of remelting is present in many of the gneisses in the vicinity of Moak Lake and Mystery Lake, in the form of pegmatitic bands in the rock. Rocks in various stages of granitization are present in this vicinity also. These phenomena all indicate that the rocks have been deeply buried; this is in accord with the theory that this zone underwent mountain-building.

If Harrison's correlation of the Kisseynew gneisses and the pre-Assean Lake gneisses of the Thompson Lake-Moak Lake area is correct, then this entire belt appears to have

undergone a mountain-building process. The belt approximates very closely the position of the structural break in the area that was previously described.

The presence of serpentinite bodies along the Split Lake-Setting Lake break is a further indication that the zone delineates a former island arc area and a subsequent mountain range. Serpentine has been found as far east as Assean Lake and Split Lake and as far south as Setting Lake. The Moak Lake serpentinite is one of these bodies. Serpentinite drill core was found by the writer along the Burntwood River east of Apussigamasi Lake. Serpentinite is known to underlie a portion of Mystery Lake. The Moak Lake orebody is in serpentinite, as is a low-grade nickel deposit in the vicinity of Ospwagan Lake. No outcrops of serpentinite were observed along this break by the writer. However, Quinn (1955) described altered basic to ultrabasic rocks which are confined to the break between Setting Lake and Ospwagan Lake. He stated that these rocks are rather sinuous, and range from 500 to 5000 feet long and from 50 to 1000 feet wide. He mentioned further that these bodies consist of pyroxenite and peridotite and are commonly serpentinized. The restriction of this type of ultrabasic rock to a major structural break (the Split Lake-Setting Lake break) and its mode of occurrence as described by Quinn are

characteristics common to ultrabasic rocks associated with island arc systems, as discussed in Chapter II. The serpentinite at Moak Lake has previously been discussed as an Alpine-type ultrabasic rock. Also, as previously stated, Hess believes that serpentinite zones are restricted to orogenic zones which were formerly island arc systems. These facts: the recognition of a serpentinite zone accompanying the structural break from Split Lake to Setting Lake, the attitudes of these ultrabasic bodies, and the recognition that the serpentinites are Alpine-type ultrabasics, all indicate that this area was formerly part of an island arc system and subsequently of a mountain range.

A negative and a positive isostatic gravity anomaly are characteristic of all island arc systems, as indicated in Chapter II. The negative anomaly in present-day island arc systems lies parallel to, and commonly over, the trough; and one positive anomaly lies to the concave side of the negative anomaly at a distance of 30 to 60 miles from it.

The Bouguer gravity map of central Manitoba accompanying this report shows that a marked gravity high paralleled by a gravity low at a distance of 25 to 40 miles to the north, lies along the break from Split Lake to Setting Lake. The gravity low corresponds closely to the position of the serpentinite belt, and the belt as a whole is concave to the southeast. These features are remarkably similar to belts of anomalies occurring with present-day island arc systems.

Two discrepancies in the comparison of these gravity anomalies with those occurring with island arc systems are obvious. One is that the intensity of the anomalies accompanying this break are much less than those associated with active island arc systems. The other discrepancy is that the positive anomaly is much more pronounced than is the negative anomaly.

Gravity anomalies in active island arc systems are believed to be a reflection of the Mohorovicic discontinuity between the crust and the mantle of the earth. The relatively small size of the anomalies in central Manitoba suggested that they may possibly be caused by density differences in the rocks within the crust. However, J. M. Patterson has compiled a map of areas which include or lie adjacent to the Thompson Lake-Moak Lake area (personal communication): the Nelson House area (Quinn, 1955), the Uhlman Lake area (Wright, 1953), the Sipiwesk area (Harrison, 1951), and the Split Lake area (Mulligan, 1955). This map shows the rock types to be relatively uniform throughout the area covered by the compilation. Therefore, the surface rocks do not account for the gravity anomalies. Because of this, it is probable that the gravity anomalies along the Split Lake-Setting Lake break are a reflection of the Mohorovicic discontinuity.

The small size of the gravity anomalies in this area compared to those associated with island arc systems is believed by the writer to be a result of isostatic adjustment

acting on the area since the island arc system became inactive. Isostasy acting over the area would tend to restore it to equilibrium, thereby obliterating the gravity anomalies. The area is still out of isostatic equilibrium, but the size of the anomalies is much reduced due to this adjustment acting through time.

SUMMARY

The high degree of coincidence of the gravity anomalies with the structural break and the persistence of the anomalies across central Manitoba indicate that the two features are related. The orogenic nature of this structural break, its association with the gravity anomalies, and the coincidence of sediments, lavas, and Alpine-type ultrabasics with it, are strong evidence that this area was once occupied by an active island arc system.

ULTRABASIC AND BASIC DYKES

The Cuthbert Lake peridotite complex and the associated dyke swarm were shown in a previous chapter to result from the same orogenic period and to have had a common source. Numerous basic dykes and some ultrabasic dykes are reported in the Split Lake area (Mulligan, 1956) and in the Sipiwesk area (Harrison, 1951). In both cases, it is reported that

the dykes are confined to the area southeast of the Split Lake-Setting Lake break. In the Uhlman Lake area (Wright, 1953) and the Nelson House area (Quinn, 1955), both of which lie to the northwest of this break, basic dykes are rare, or absent. The location of these dykes is apparently controlled by the Split Lake-Setting Lake break.

It is not known if the forces which caused the fractures now occupied by these dykes were related to the forces acting during the active stage of the island arc system. The control exercised by the break on the location of the dykes indicates that the forces were related. If this were so, the dykes must have been intruded during the waning stages of the island arc system, as they show only minor metamorphic effects.

The origin of the magma giving rise to these dykes must necessarily remain unknown. However, in describing the West Indies island arc system, Officer (1957) postulated that the Caribbean area is in the process of conversion from an oceanic area into a continental area by the intrusion of basic and acid magmas, and andesitic lavas. Perhaps the magma giving rise to the basic and ultrabasic dykes of the Cuthbert Lake area was a basic magma of this type, which originated during the tectonics of the area. This must remain only a suggestion. However, the evidence does suggest that the magma giving rise to these dykes was associated with the tectonics of the island arc system which once existed in

the area.

ECONOMIC SIGNIFICANCE

Economic nickeliferous sulphide deposits in the Thompson Lake-Moak Lake area are associated with or related to the bodies of ultrabasic rocks located along the Split Lake-Setting Lake break. No similar deposits of economic importance have been found associated with the Cuthbert Lake peridotite complex. As the Moak Lake and Cuthbert Lake ultrabasic rocks are considered to have had different origins, it cannot be assumed that, because sulphide deposits are associated with one type of rock, they are necessarily associated with both types. In fact, no sulphides have been found in the Cuthbert Lake peridotite, and only minor showings are found associated with the basic dykes of the dyke swarm.

The two chemical analyses of the Cuthbert Lake rocks perhaps indicate why this is the case. The rocks of the Cuthbert Lake peridotite complex contain appreciable nickel (0.48 per cent), while the analysed specimen of the basic dykes contains but a trace. These values agree with those reported by Goldschmidt (1954, p. 670) for similar rock types in which the ratio of nickel in basic rocks as compared to ultrabasic rocks is approximately 1:20. Goldschmidt's average value for the nickel content in ultrabasic rocks is 0.36 per cent. Nickel is concentrated in the olivine minerals

where it replaces the magnesium ion. For this reason, it is concentrated in rocks of the ultrabasic group.

The concentration of sulphur in the Cuthbert Lake dyke rocks is low; a value of 0.07 per cent was reported for the sample of ultrabasic rock analysed, and none was reported for the analysed basic rock. H. D. B. Wilson (1953, p.390) has constructed a graph which shows the relation between sulphur solubility and the percentage of silica in silicate melts (based on Vogt's data). This provides a possible explanation of why economic sulphide deposits are not found associated with the Cuthbert Lake peridotite. According to the graph, a silicate melt containing 45 per cent silica will dissolve between 0.3 and 0.4 per cent sulphur. The ultrabasic rocks of Cuthbert Lake did not, in all probability, contain enough sulphur for a liquid sulphide phase to form. Thus nickel present in the magma became incorporated in the early-forming silicate minerals, notably olivine, where it remained. Intrusion of this early-formed, nickel-rich phase could have occurred before differentiation had proceeded far enough for an immiscible sulphide liquid to segregate from the silicate melt. That the early intrusion of the first formed olivine-rich phases occurred is supported by the fact that two generations of olivine, as previously discussed, are present in some thin sections. If, during this early stage of crystallization, nickel was incorporated in the olivine crystals, then intrusion of this phase at an early stage of

differentiation would remove nickel from the system. This would prevent it from selectively entering the immiscible sulphide liquid, if, indeed, such a liquid did form. In addition, small scattered showings of sulphides, mainly chalcopyrite with minor pyrrhotite associated with the accompanying basic dykes indicate that the separation of a sulphide liquid took place at the time these rocks were being differentiated. Such showings remain insignificant despite recurring exploration in the area, suggesting that the immiscible sulphides separating from the magma were not concentrated in such quantity as to form a nickel deposit of economic importance.

Nickel could have been effectively removed from the system in the subterranean magma chamber. Crystal settling of olivine and its accumulation on the floor of the chamber could possibly have removed it from reaction with a later-forming immiscible sulphide liquid. However, intrusion of a crystalline mass of this type would supposedly be brought about with some mineral granulation. Evidence for this was not seen in any of the thin sections examined. Of the two hypotheses put forth, therefore, the first appears more plausible than the second.

Chemical analyses of the Moak Lake serpentinite and the Cuthbert Lake peridotite indicate that both these rock types contained nickel at the time of their intrusion. Nickel in the Moak Lake-type of ultrabasic rock has been

concentrated to form economic sulphide deposits. Whether this concentration took place during emplacement or at some later stage in the rock's history is beyond the scope of this paper. If this concentration is a result of processes subsequent to intrusion of the rock, these processes have not acted on the Cuthbert Lake dyke swarm, as only local deformation has affected the dykes. That the two rock types have undergone different processes is quite possible, as their origins, and probably the times of their emplacement, differ greatly. The hypothesis presented in this chapter is that the lack of economic sulphide deposits associated with the Cuthbert Lake rocks can be explained by a deficiency of sulphur in the original magma.

CHAPTER V

CONCLUDING STATEMENT

A study of the literature on ultrabasic rocks indicated that several distinct types of occurrences of these rocks exist. The Alpine-type and the Bushveld-type peridotites were identified and discussed in the preceding chapters. It was pointed out that Alpine-type peridotite is found associated with present-day island arc systems or compressional mountain ranges and their eroded roots; whereas Bushveld-type peridotite originates from the crystal differentiation of a basic magma.

A study was made of the structure, petrography, and chemical composition of the ultrabasic and basic dykes of the Cuthbert Lake area. The writer concluded that the dykes represent different phases of a differentiated basic magma.

The distribution of the joint sets on outcrops of the Cuthbert Lake peridotite complex was studied. It was concluded that the complex consists of a series of dyke segments arranged in an "en echelon" pattern and not as a single dyke as Dawson had previously mapped it.

On the basis of Hess's distinctions between Alpine-type peridotite and Bushveld-type peridotite, it was shown that the Moak Lake serpentinite corresponds to the Alpine-type peridotite; the Cuthbert Lake peridotite complex, to the

Bushveld-type peridotite.

The evidence presented to show that the Split Lake-Setting Lake break marks the trace of an old island arc system is inconclusive. It is quite possible that valid arguments can be amassed to contradict this hypothesis. However, this hypothesis appears to comply most completely with the facts available to the writer.

The ultrabasic rocks of Moak Lake and Cuthbert Lake are Alpine-type and Bushveld-type peridotites, respectively. Their origins, therefore, differ greatly. From the distribution of known nickel occurrences in the area, it appears that the Moak Lake type of ultrabasic rocks contained nickel when they were intruded. The Cuthbert Lake ultrabasic rocks, on the other hand, have no known economic nickel deposits associated with them. The reason for this appears to be that the magma from which they originated did not contain the necessary sulphur to form nickel sulphide deposits.

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PLATES

The abbreviations used to describe the minerals in the accompanying photomicrographs are as follows:

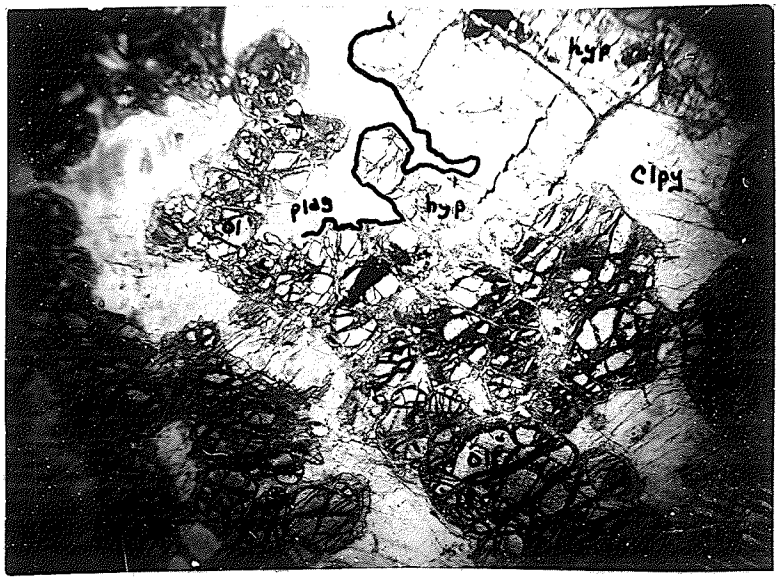
Olivine	Ol.
Hypersthene	Hyp.
Clinopyroxene	Clpy.
Plagioclase	Plag.
Hornblende	Hb.
Serpentine	Serp.
Pyrrhotite	Py.
Magnetite	Mag.

Plate I



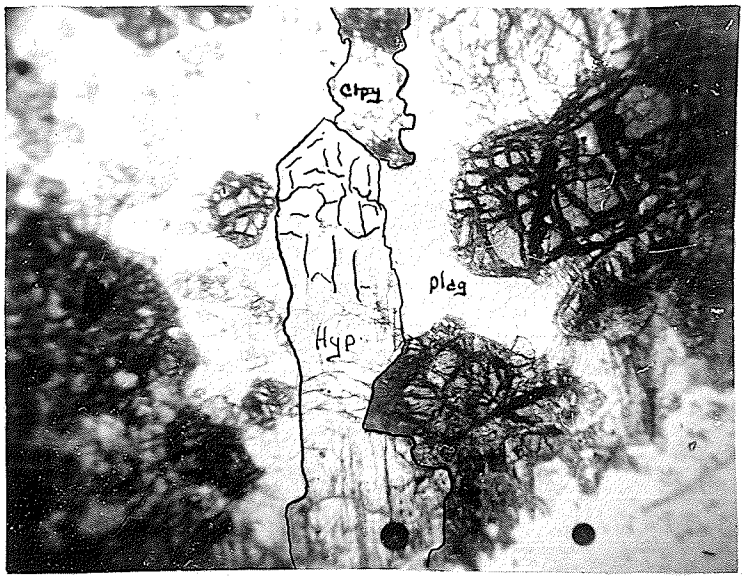
Cuthbert Lake peridotite. Early-formed olivine enclosed by later, well-formed plagioclase. Hornblende forms the matrix and is the last mineral to crystallize. M-451-A-58. Plain light (x70).

Plate II



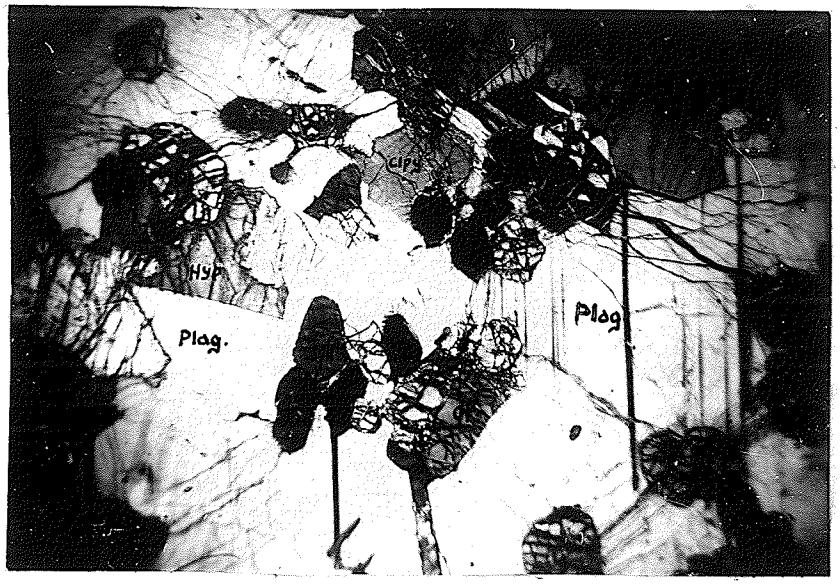
Cuthbert Lake peridotite. Euhedral and subhedral olivine grains grouped in clusters. Euhedral hypersthene and later clinopyroxene surround it. Plagioclase is interstitial. M-667-A-58. Plain light (x25).

Plate III



Cuthbert Lake peridotite. A large crystal of hypersthene partially formed around olivine. Later clinopyroxene forms against hypersthene. Plagioclase is interstitial. M-602-58. Plain light (x25).

Plate IV



Cuthbert Lake peridotite. Euhedral crystals of olivine with later subhedral crystals of hypersthene and clinopyroxene. Plagioclase is well-crystallized and is the last mineral to form. M-486-A-58. Crossed nicols (x34).

Plate V



Cuthbert Lake peridotite. Olivine is shown altering to both serpophite and antigorite. Remnants of olivine and the outline of original olivine grains are apparent. The veinlet of magnetite is secondary and has been derived from the alteration of olivine. M-451-A-58. Plain light (x104).

Plate VI



Cuthbert Lake peridotite. Euhedral grains of olivine set in a matrix of ophitic hornblende. Small mineral fragments in the hornblende are primarily olivine with minor hypersthene and clinopyroxene. Note the large variation in grain size of the olivine. M-457-58. Crossed nicols (x28).

Plate VII



Contact between a peridotite dyke and the paragneiss from Cuthbert Lake. Note the fine-grained nature of the dyke matrix, probably re-crystallized glass. Large, euhedral olivine grains are aligned roughly parallel to the contact and are the only identifiable grains present. The contact is knife-edged. P-596-B-58. Crossed nicols (x26).

Plate VIII



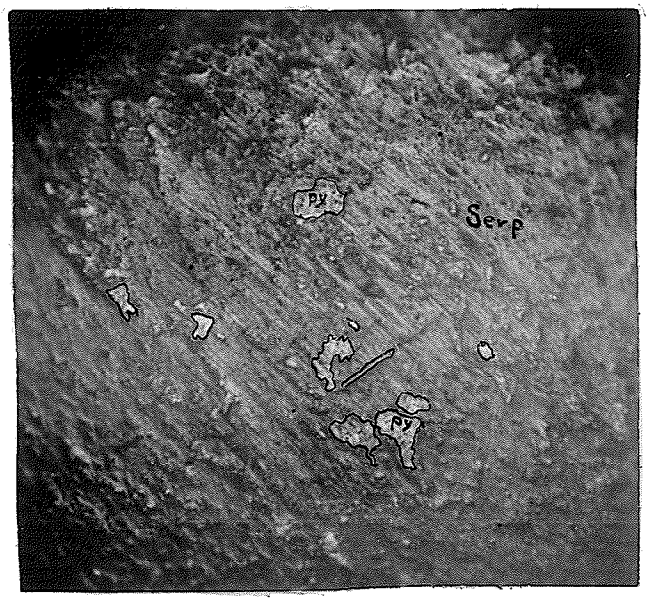
Typical diabasic texture of the basic dykes forming the Cuthbert Lake basic dyke swarm. Note the "dusty" appearance of the plagioclase lathes and their corroded edges where hornblende surrounds them. M-544-A-58. Crossed nicols (x27).

Plate IX

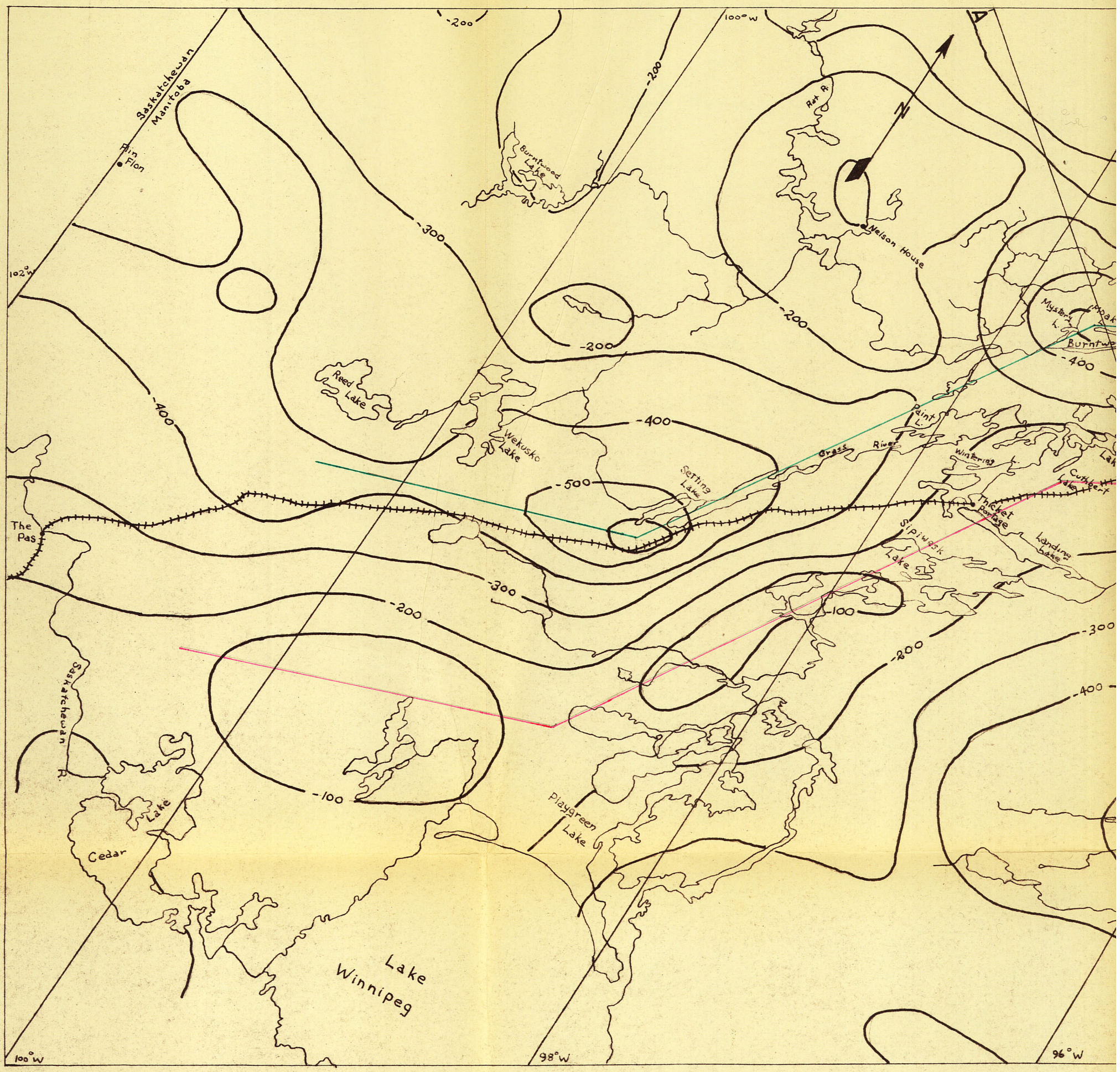


Pseudomorphs of serpentine after olivine from a section of the Moak Lake serpentinite. Note the strong preferred orientation and the delicate mesh structure. The matrix (black) is a fine-grained aggregate of serpentine. D.D.H. # 11326 (550 feet). Crossed nicols (x22).

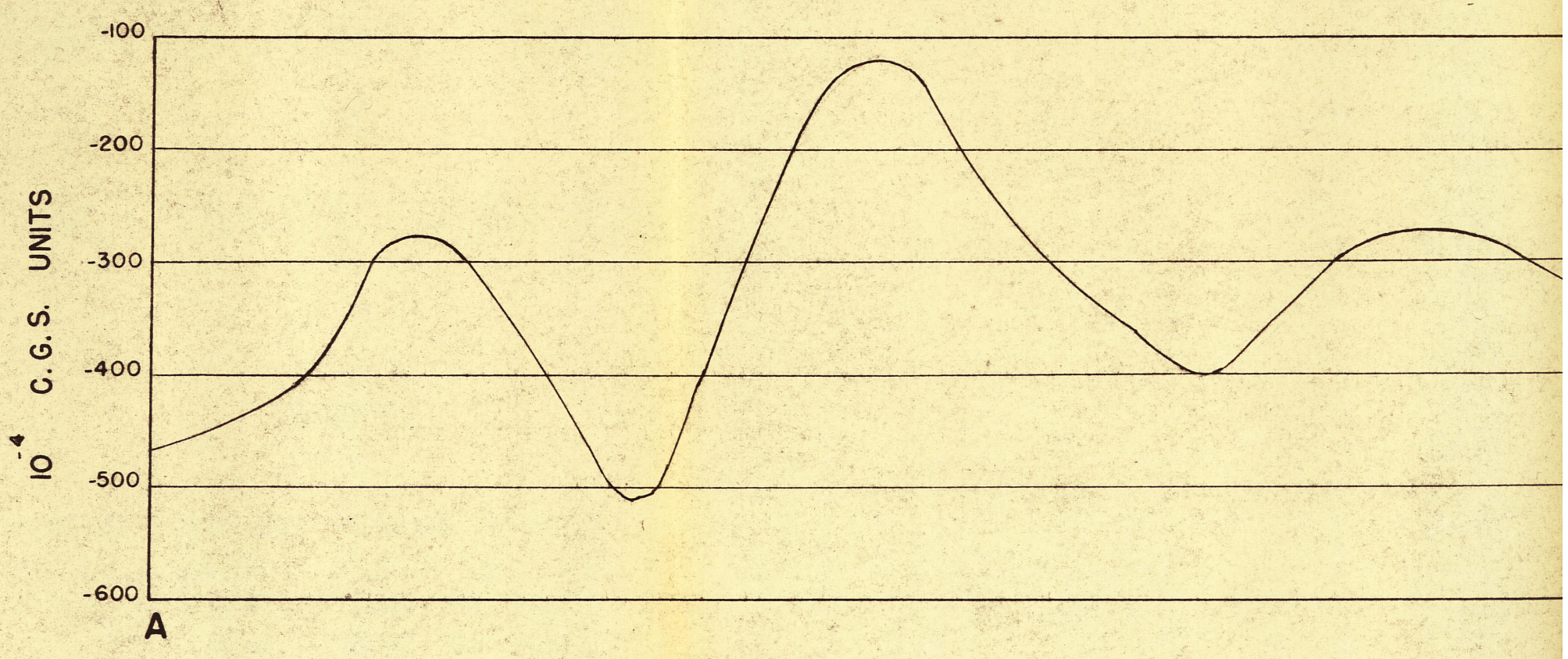
Plate X



A polished section surface showing the distribution of pyrrhotite grains in the Moak Lake serpentinite. D.D.H. # 12993 (610 feet). Plain light (x11).



BOUGUER ANOMALY



GRAVITY PROFILE – A to B

98° W

96° W

94° W

Churchill River

-400

-300

-300

-400

-500

-400

River

Split L.

Begg L.

Hudson Bay Railway (C. N. R.)

Nelson River

-200

Lake Utik

Bigstone River

-500

-600

Oxford Lake

Oxford House

-300

Knee L.

Hayes River

94° W

92° W

B

GRAVITY ANOMALY MAP OF CENTRAL MANITOBA

LEGEND

-300 GRAVITY ANOMALY CONTOUR (INTERVAL 100×10^{-4} C. G. S. UNITS)

TRACE OF GRAVITY HIGH

TRACE OF GRAVITY LOW

SCALE : ONE INCH TO TWENTY MILES

FROM: CANADIAN DEPARTMENT OF MINES & TECHNICAL SURVEYS MAPS - 1952

BEGG

LAKE

TRUE NORTH

MAGNETIC NORTH

MAGNETIC DECLINATION
9° 10' EAST

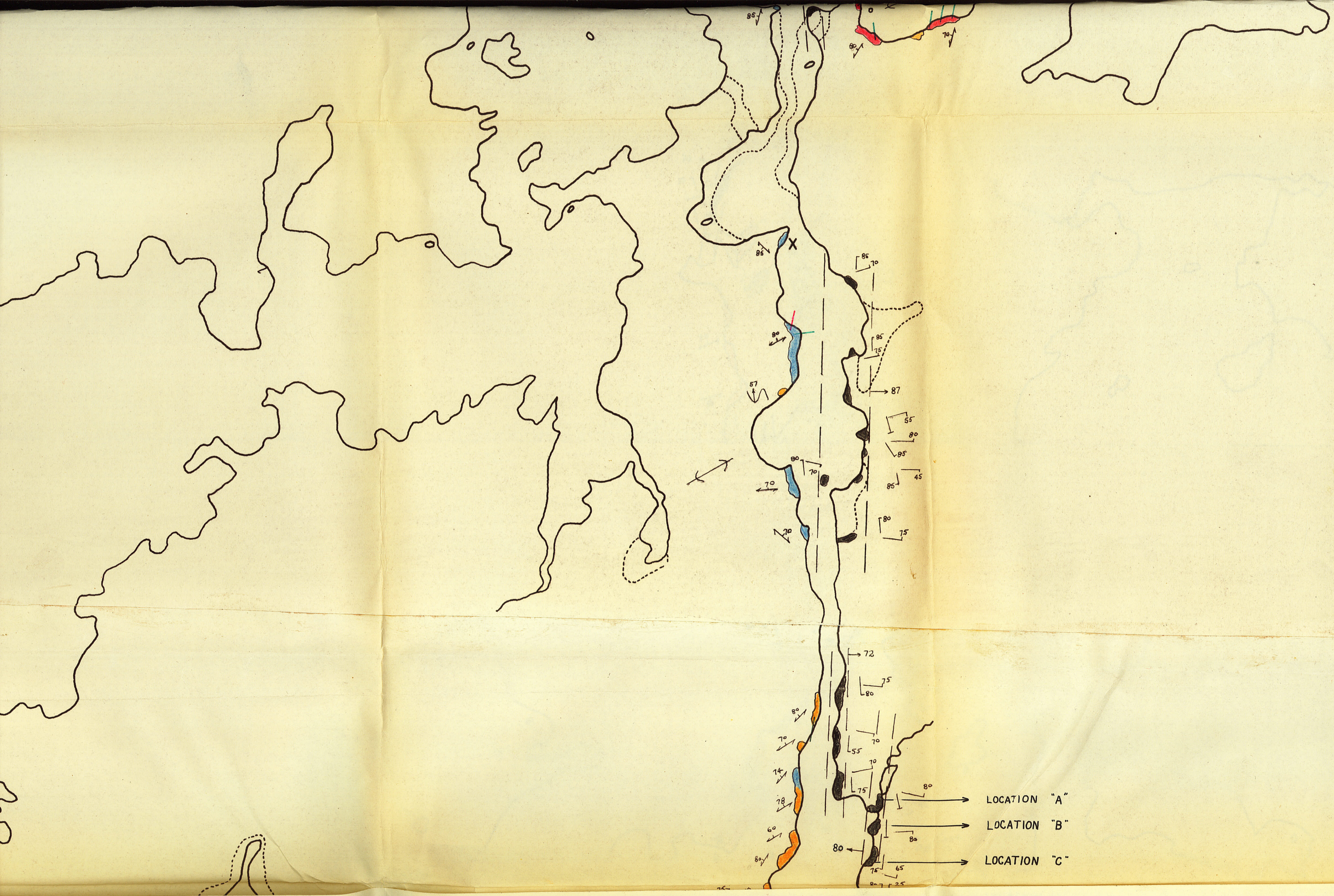
BUCKINGHAM

LAKE

AWAHUNAN

NATAWA

LAKE


LOCATION "A"
LOCATION "B"
LOCATION "C"

LAKE

CUTHBERT

GEOLOGY
of the
UTHBERT LAKE AREA

LEGEND

vine diabase

Gabbro
Diabase

ridotite

SYMBOLS

Gneissocity (inclined, vertical, unknown)

Joint (inclined, vertical)

Fault (inclined, vertical, unknown)

Shear (incli... vertical

GEOLOGY
of the
CUTHBERT LAKE AREA

LEGEND

- Olivine diabase
- a) Gabbro
  b) Diabase
- Peridotite
- Plagioclase amphibolite
- Orthogneiss
- a) Paragneiss
  b) Limestone and quartzite

SYMBOLS

- Gneissocity (inclined, vertical, unknown)
- Joint (inclined, vertical)
- Fault (inclined, vertical, unknown)
- Shear (inclined, vertical, unknown)
- Drag fold (arrow indicates plunge)
- Dyke segment boundaries (inclined, unknown)
- Mineral showing
- Swamp
- Glacial striae

1000 500 0 1000 2000 3000 4000 5000

Scale: 1 inch = 1770 feet or 1:21,240

