BULLETIN 77

GEOLOGICAL
SURVEY
OF
CANADA

DEPARTMENT OF MINES
AND TECHNICAL SURVEYS

PETROLOGY AND GEOCHEMISTRY OF THE GRIFFIS LAKE ULTRABASIC SILL OF THE CENTRAL LABRADOR TROUGH, QUEBEC

W. F. Fahrig

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PREFACE

In 1950 the Geological Survey of Canada began geological mapping of a continuous strip across the Labrador Trough. The Griffis Lake area occupies the eastern end of this strip, and was mapped in 1950 and 1951. Detailed study of the ultrabasic rocks in that area has provided the material for this bulletin.

The ultrabasic rocks that outcrop in the Griffis Lake area are part of a suite that extends for about 60 miles along the east side of the Labrador Trough and are similar to ultrabasic rocks of the Cape Smith belt in which large showings of asbestos have recently been reported.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, October 5, 1960

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PETROLOGY AND GEOCHEMISTRY OF THE GRIFFIS LAKE ULTRABASIC SILL OF THE CENTRAL LABRADOR TROUGH, QUEBEC

Abstract

'Alpine-type' peridotite sills occur in the predominantly volcanic sequence along the eastern side of the Labrador Trough. Individual sills are more than 2,000 feet thick, and have been traced for more than 20 miles along strike. One of these, the Griffis Lake sill, is described in detail.

The ultrabasic rocks probably were originally feldspathic peridotite, with 50 to 60 per cent olivine, but were intensely serpentinized and later locally steatitized along structurally controlled zones. Olivine crystals in the sills show a preferred orientation, which, in the absence of evidence of fractional crystallization or of high temperature contact effects, suggests intrusion of olivine crystals in a silicate liquid of gabbroic composition. The lower and upper parts of the sills are more gabbroic than the central parts, very likely because of mechanical crowding of olivine crystals towards the central part of the sills during intrusion. Nickel is almost twice as abundant as chromium in the Griffis Lake sill, which is probably the result of extreme differentiation of basic parent magma prior to the intrusion of the ultrabasic material. Most of the ultrabasic sills are overlain by thick gabbro sills, but chemical data suggest that the ultrabasic rocks and the gabbros were intruded independently and are not the result of fractional crystallization in place. The ultrabasic rocks may have been intruded prior to or during the folding of the enclosing volcanic rocks.

Résumé

Des sills de péridotite du type alpin se rencontrent dans la succession de roches en grande partie volcaniques qui se trouve le long du versant est de la fosse du Labrador. Certains sills atteignent une épaisseur de plus de 2,000 pieds et ont été reconnus le long de leur direction sur une distance de plus de 20 milles. L'un deux, le sill du lac Griffis, fait l'objet d'une description détaillée.

Les roches ultrabasiques étaient probablement constituées à l'origine de péridotite feldspathique, renfermant entre 50 et 60 p. 100 d'olivine, mais elles ont été fortement serpentinisées et, par la suite, stéatitisées en certains endroits le long de zones reliées à la tectonique. Les cristaux d'olivine présents dans les sills démontrent une orientation dominante qui, faute d'indices de cristallisation fractionnée ou d'effet dûs aux températures élevées des zones de contact, laisse croire à une intrusion de cristaux d'olivine au sein d'un liquide silicaté de composition gabbroïque. Les zones inférieures et supérieures des sills sont plus gabbroïques que celles du centre, très probablement en raison de la concentration mécanique des cristaux d'olivine vers la partie centrale des sills au cours de l'intrusion. Le sill du lac Griffis renferme près de deux fois plus de nickel que de chrome, par suite, probablement, de la différentiation extrême du magma basique originel, qui a précédé l'intrusion des roches ultrabasiques. La plupart des sills ultrabasiques sont recouverts d'épais sills de gabbro, mais les données chimiques laissent croire que les roches ultrabasiques et les gabbros ont été injectés indépendamment et qu'ils ne résultent pas de la cristallisation fractionnée en place. Il se peut que les roches ultrabasiques aient été injectées antérieurement ou simultanément au plissement des roches volcaniques encaissantes.

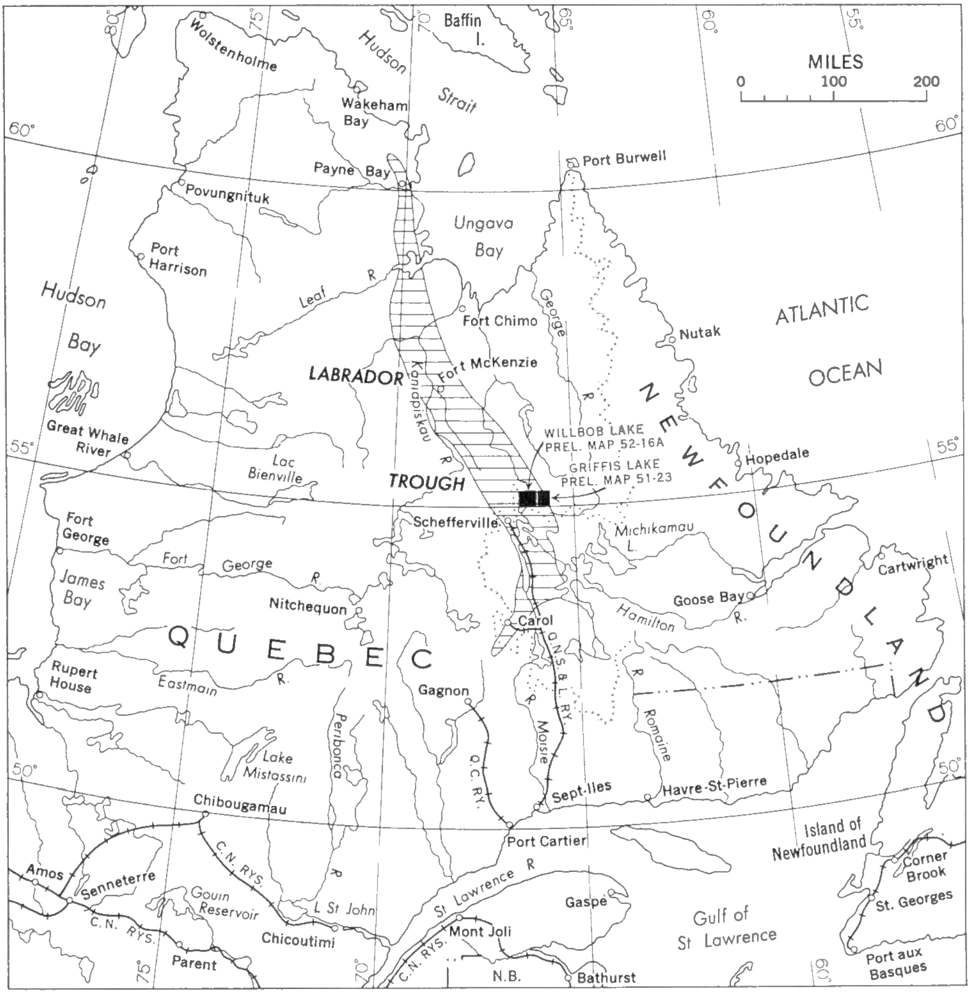

Figure 1. Map showing location of Labrador Trough and areas (in black) described in Geological Survey of Canada Papers 51-23 and 52-16A.

INTRODUCTION

During the summers of 1950 and 1951 the writer mapped Griffis Lake map-area (lat. 55° 00′ to 55° 15′; long. 65° 30′ to 66° 00′) for the Geological Survey of Canada on a scale of 1 mile to the inch. This map-area lies on the eastern border of the Labrador Trough (Fig. 1), which is a belt of igneous and sedimentary rocks extending more than 600 miles southeast from the west shore of Ungava Bay. The Trough is generally less than 50 miles wide, and is composed on the west of a 3,000-foot sequence of shallow-water sediments, and on the east of more than 10,000 feet of basic intrusive and extrusive rocks.[1]

Part of the basic igneous belt in the east consists of a zone of serpentinite sills that occur over a width of nearly 25 miles at latitude 55° 07′ and longitude 66° 00′. Its southward extension from this point is not great, probably about 10 miles; it extends northwest for about 50 miles (*see* Fig. 2).

A study of the ultrabasic rocks in the west half of Griffis Lake map-area was presented as a Ph.D. thesis to the University of Chicago (Fahrig, 1953) and this report is part of that thesis. There were no published accounts of the geology of the ultrabasic rocks of the Labrador Trough when the writer made his study.

Grateful acknowledgment is tendered to Dr. Hans Ramberg for his critical advice during the preparation of the thesis. Mr. Oiva Yoensu gave much assistance and advice in spectrographic determinations and many helpful discussions were carried on with R. A. Robie and H. D. Woodard at the University of Chicago.

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[1] For a brief description of the Labrador Trough the reader is referred to Harrison (1952). The geology of specific areas within the Trough is given in Frarey (1952), Fahrig (1951, 1955, 1956), and Baragar (1958).

GENERAL GEOLOGY

Mode of Occurrence

The major field relations of the Quebec-Labrador ultrabasic rocks are illustrated in Figure 2. The sills, numbering four or five in the section shown, have a maximum thickness of about 2,000 feet, which is remarkably constant along strike, and are invariably concordant with the surrounding rock structure. Individual sills extend continuously for a distance of more than 20 miles.

Typically, the ultrabasic rocks are overlain and less commonly underlain by meta-gabbros, but in places they intrude meta-basalts or sediments. Towards the western part of the area shown, the terrain is predominantly sedimentary and this has to some extent influenced the mode of intrusion of the ultrabasic rocks. The intrusions there are more numerous, thinner, and less continuous than those within the thick lava flows and gabbros in the central part of the area. Outcrop is poor in the metamorphic rocks to the east, but ultrabasic rocks seem to occur there in thin possibly discontinuous bodies.

The nature of these ultrabasic rocks, particularly their constant thickness and great lateral extent, suggests the rapid injection of highly fluid material. The meta-gabbro overlying almost all the sills suggests a differentiation in place.

Structural Setting

The ultrabasic rocks and their country rocks have been folded and faulted by forces acting from a N45°E direction. The result is a series of folds of large magnitude (4 or 5 miles), whose axial planes dip steeply northeast. Drag-like smaller folds are superimposed on these major flexures. Thrust faults, related to this major deformation, strike northwest and dip at a moderate to steep angle northeast. Minor fracture zones with negligible displacement intersect the folds and have a direction about 30 degrees to the assumed direction of compression. These minor faults are particularly noticeable on aerial photographs where they cross massive meta-gabbro and ultrabasic intrusions. One such cross-fracture having a greater than usual extent and a displacement of about 350 feet is shown on Figure 3. The strikes of the major faults converge towards the south and southeast.

Possibly the most striking structural feature in this section of the Trough is the consistent plunge of the fold elements towards the southeast. Within any thrust slice younger formations are exposed in mapping to the southeast, which improves the possibility of making stratigraphic correlations across the major thrusts. It is not known whether this southeast plunge is characteristic of more than a local section, but it seems likely that it will continue along the eastern part of the Trough. Towards the western border of the area shown in Figure 2 a number of asymmetrical minor folds plunge to the southeast.

Lithology of the Country Rocks

Members of the Doublet group (Fahrig, 1951; Frarey, 1952; Harrison, 1952) form the eastern part of the central section of the Labrador Trough. This group is

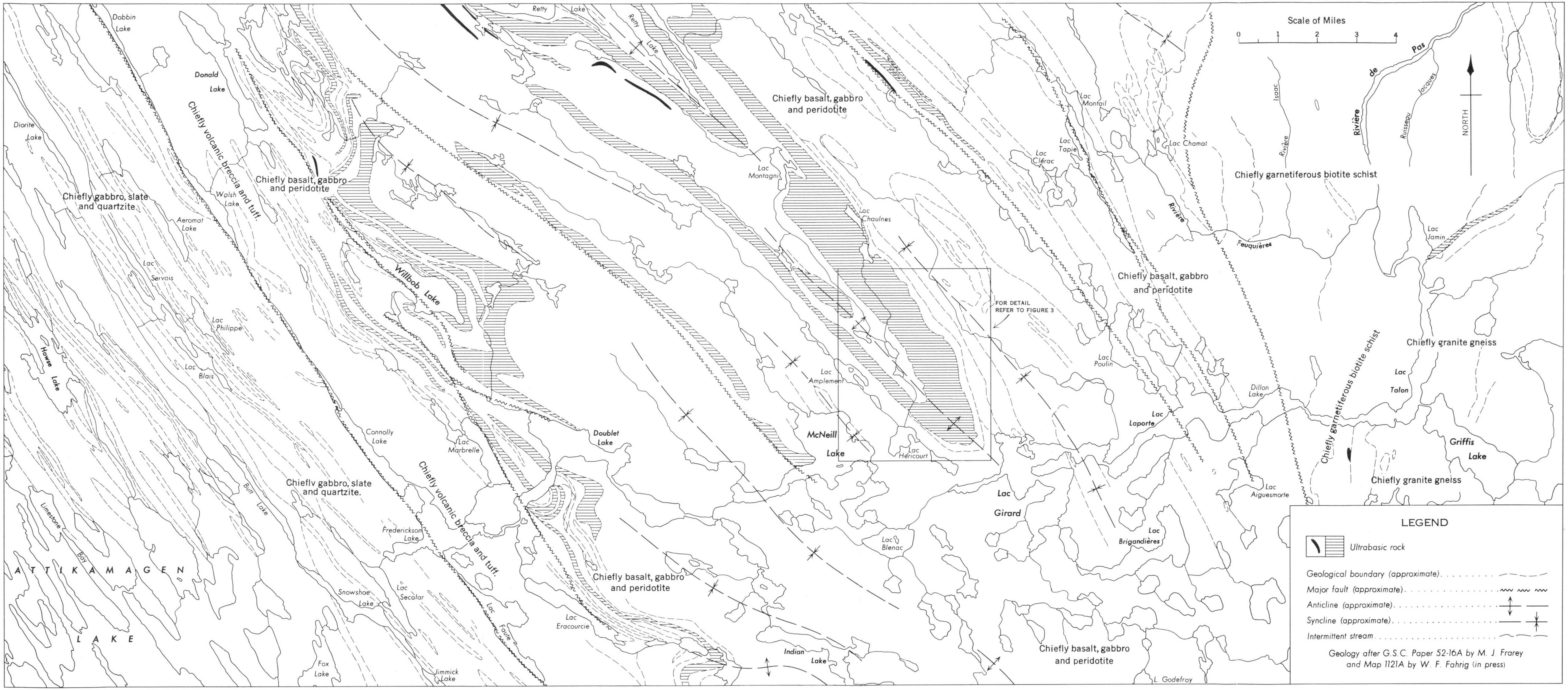

FIGURE 2. Generalized geology across the ultrabasic belt, Willbob and Griffis Lake map-areas

composed of pillow lavas and tuffs with minor shallow-water sediments, quartzites, conglomerates, and shales. Of these, pillow lavas form the dominant members, particularly if fine-grained, unpillowed layers of basaltic composition (in part intrusive) are grouped with them. As indicated in Figure 2, the sediments are restricted mainly to the western parts of the belt. The meta-basalts and meta-gabbros of the Doublet group generally form the country rocks for the ultrabasic intrusions, and are the only rocks that might have a genetic relationship to them.

The meta-basalts form a series upwards of 10,000 feet thick, are fine grained, light green or grey, vary but little in composition, and are almost universally pillowed. Chlorite, calcite, quartz, and chert form the material between the pillows.

In thin section the meta-basalt is seen to be a mesh of pale green actinolite and clinozoisite. The actinolite, substituting entirely for the original mafic minerals, is pale green and is in the form of irregularly terminated needles and similar more equidimensional crystals. The latter reflect the shape of earlier pyroxenes. The actinolite shows wavy extinction. The clinozoisite in these lavas is almost colourless, and shows inclined extinction and anomalous blue interference. It generally has an irregular crystal habit and typically forms lath-like patches pseudomorphic after earlier basic plagioclase. Varying amounts of chlorite, feldspar, biotite, magnetite, and titanite occur in the meta-basalt. The plagioclase is generally secondary, usually in the form of clear interstitial patches with maximum extinction on (010) of 16 degrees; its composition, therefore, is An_{34}. In some sections pseudomorphs of early plagioclase are present. They are now an almost opaque mass of fine-grained alteration products. Small flakes of pleochroic yellow biotite are observed in most slides.

The regional metamorphism is thus representative of low epidote-amphibolite facies.

The meta-gabbros are coarse-grained equivalents of the lavas, and are similar to them in most respects. Some contain fairly large patches of blue-green hornblende, surrounded by actinolite and partly replaced by biotite. The blue-green hornblende is probably a retrograde mineral.

A composite analysis of the pillow lavas is given in Tables I and II, along with Daly's average for plateau basalt and diabase. Chemically, the meta-basalts are most closely related to the tholeiitic, quartz diabase association. Examples of such basalt provinces are the Keweenawan lavas of Lake Superior, and the Deccan plateau basalts. The chemical characteristics that set the tholeiitic basalts apart from the olivine basalt magma types are a tendency for higher SiO_2 and lower Na_2O, K_2O, and MgO (Turner and Verhoogen, 1960). This chemical characteristic is exhibited by the Quebec-Labrador volcanic rocks, which show, as a result, an appreciable quantity of normative quartz. The most striking feature of the analysis is probably the low Na_2O content. The association of greywacke sediments and spilitic volcanic rocks with so-called 'Alpine' ultrabasic rocks has been commented on by many writers (Hess, 1938). In the area under discussion, however, both greywacke and spilitic lavas are rare. Nevertheless, this does not imply that the ultrabasic rocks are not of the 'primary ultramafic' or Alpine type as defined by Hess.

Megascopic Description

Zoning

The ultrabasic sills exhibit a striking megascopic zoning parallel to their borders. These zones (*see* Fig. 3) are gradational one into the other and split the sill into the following three megascopic types:

1. Outer border zones—or actinolite zones
2. Intermediate zones—highly serpentinized
3. Central zone—containing olivine.

Table I

Comparison of Doublet Meta-Basalts with Daly's[1] Average For Diabase and Plateau Basalt

—	Plateau Basalt	Diabase	Meta-basalt—Labrador*
SiO_2	48.80	50.48	49.86
Al_2O_3	13.98	15.34	15.07
Fe_2O_3	3.59	3.84	2.39
FeO	9.78	7.78	9.63
CaO	9.38	8.94	9.64
MgO	6.70	5.78	6.34
Na_2O	2.59	3.02	1.76
K_2O	0.69	0.97	0.43
H_2O	1.80	1.89	3.18
H_2O-	—	—	0.34
TiO_2	2.19	1.45	0.53
P_2O_5	0.33	0.25	0.20
MnO	0.17	—	0.37
S	—	—	0.15
	Sp. gr. = 2.93	Sp. gr. = 2.96	Sp. gr. = 3.03

* Analyst: R. Fabry, Geological Survey of Canada.

[1] Daly, 1933.

Table II

Normative Minerals of Doublet Meta-Basalt

Mineral	Per Cent	Oxide Ratios
Quartz	5.81	
Orthoclase	2.22	
Albite	15.72	$\frac{MgO}{CaO}=0.66$
Anorthite	33.08	
Hypersthene	20.32	
Diopside	17.11	
Magnetite	3.71	$\frac{MgO}{FeO}=0.66$
Ilmenite	1.06	
Pyrite	0.23	

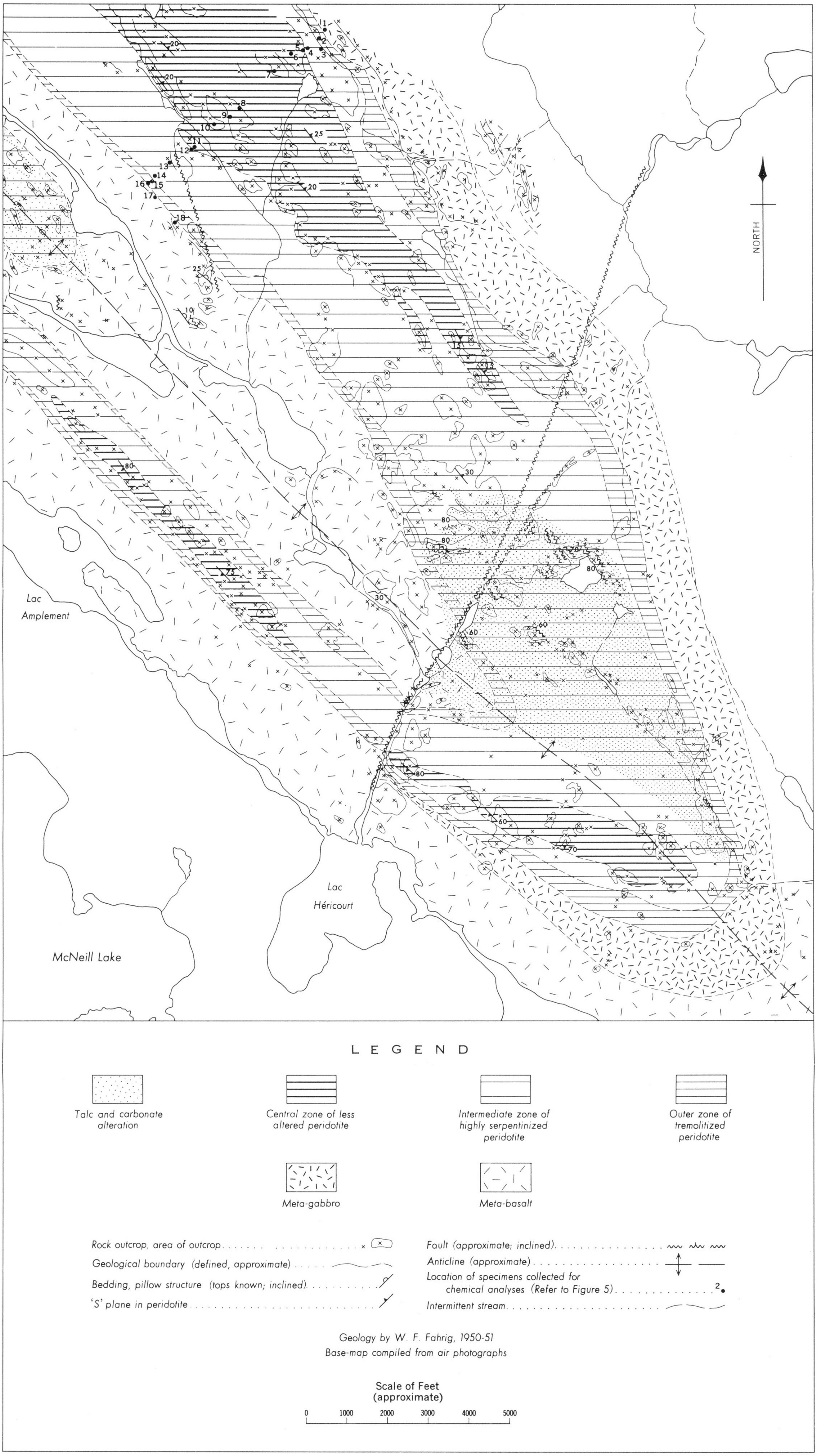

FIGURE 3. Detailed geology of the Griffis Lake folded peridotite sill northeast of McNeill Lake

The outer (border) zones are found consistently at the bottom and top of all the sills and are characterized by a rust-brown weathered surface on which more resistant actinolite or tremolite crystals stand in a relief of about 2 mm. These actinolite crystals are equidimensional, pale green or white weathering, and up to 1 cm in diameter. They form from 15 to 80 per cent of the rock and their resistance to weathering results in a 'warty' appearing outcrop surface. Although they are essentially similar at the bottom and top of the sill there are some megascopic differences. The layer at the top of the sill is usually thicker and the actinolite crystals are usually larger. It is in the upper layer that actinolite in places forms up to 80 per cent of the rock; these actinolite crystals are clearly pseudomorphous after pyroxene. The possibility of using this criterion to distinguish between the basal and upper zones could be important. Apart from the texture above described, the border zones of the ultrabasic rocks appear essentially structureless. Within each zone there is no evidence of compositional banding, but in places joint planes parallel to the walls of the sills seem somewhat more common than those of random strike and dip.

The intermediate zone has two similar parts lying next to and grading into the outer zone (Fig. 3). The weathered surface of the rock in the intermediate zone is relatively smooth, showing no differential weathering of mineral constituents. It is characteristically lighter weathering than the outer zone, most commonly in shades of rust, light brown, pink, and green. These areas of varying colour appear to be quite irregular. The writer believes that the colour variation on the glaciated surfaces must be mainly due to the diffusion of iron during serpentinization, those parts lacking a rust-weathered surface probably being lower in iron oxide. The rock in this zone is particularly tough, giving conchoidal fracture surfaces with flakes of pale green serpentine. As in the border zone, this rock is massive though highly fractured (jointed). The parting planes, however, show little consistency in orientation.

The third zone in the ultrabasic rocks is the central or olivine-bearing zone. Where present, it lies towards the centre of each sill, more often near the top than near the bottom. Being the least altered (serpentinized) of all the zones, it shows more of the primary textural features. The weathered surface is an evenly coloured, dark rust-brown. The rock, in outcrop, has a strikingly layered appearance, caused by differential weathering along minute cracks (parting planes), and produced by the occurrence on the weathered surface of fairly continuous grooves spaced from a millimetre to a few inches apart. There is no megascopic indication of compositional variation from one layer to the next. The layers apparently strike and dip parallel to the walls of the intrusive rock. In Figure 3, for example, these 'S' planes dip at 15 to 20 degrees in the east limb of the anticline and at 60 to 80 degrees in the west limb, reflecting the overturning of the anticline towards the southwest. There is also a less continuous pattern of parting at right angles to the first, more prominent set, and including the line of dip of the sills. This parting is visible only on the weathered surface. Both patterns are shown in Plate I. The rock in this central zone fractures more readily than does the rock in the outer two zones. The fracturing is controlled by the hair-like parting planes in the rock.

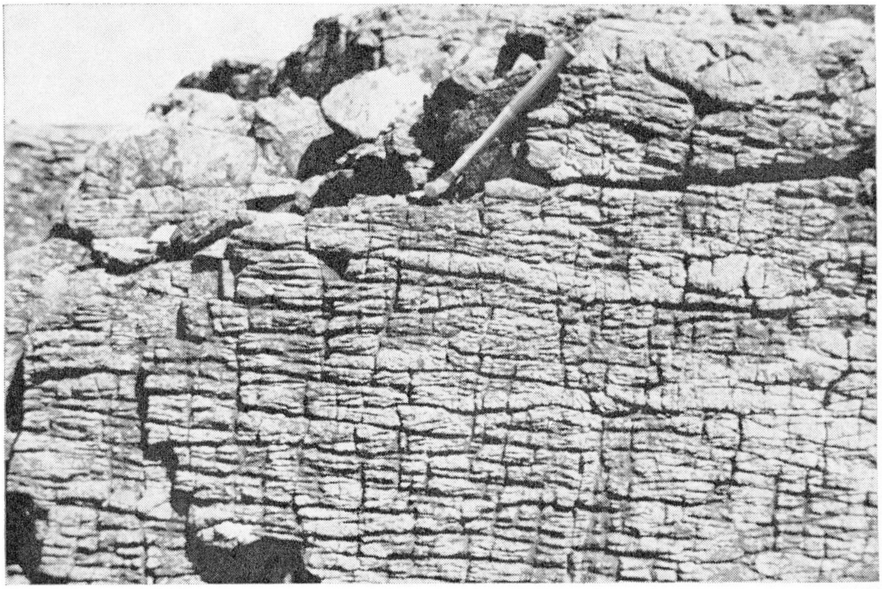

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Plate I. *Weathered surface of partly serpentinized peridotite. The irregular gently dipping planes may represent shear surfaces formed during the intrusion of an olivine mush. The vertical planes are tension joints resulting from stretching parallel to the axis of the Griffis Lake anticline.*

Patches within the central zone also show an unusual type of weathering, in that the rock locally breaks down into piles of rough, grey, pebble-sized fragments. These represent one or more pyroxenes in which are embedded numerous olivine crystals.

The irregularity of the central zone and its tendency to parallel the contacts of the sill are notable characteristics (Fig. 3). It is also notable that there is no indication of rhythmic mineralogical layering in these sills.

In summary, the ultrabasic sills of Quebec-Labrador have a large-scale megascopic zoning, which is symmetrical about a plane parallel to the walls of the sill and passes through a central less serpentinized core. The outermost zones are characterized by much actinolite, the intermediate zones by intense serpentine alteration and the central zone by a relative lack of either of these types of alteration. This large-scale zoning reflects the movement of material mainly at right angles to the surface of the walls. The irregular unserpentinized central zone suggests that water was transported inward from the walls. The movement of other materials is discussed more quantitatively under chemical composition and variations of the sills.

It was hoped that the position of the relatively unaltered central zone would give a clue to indicate whether serpentinization was post- or pre-folding. If serpentinization was post-folding the unserpentinized zone in the gently dipping limb would have a position different from that in the steeply dipping limb. This hypothesis could not be tested, however, for the western limb (Fig. 3) is overlain by meta-volcanic rocks rather than by meta-gabbro, which could have an unknown effect on the movement of serpentinizing 'solutions'. Further study in this belt might discover an asymmetrically folded ultrabasic sill with limbs bounded by a similar rock type in which the position of the unserpentinized central zone could be carefully measured to ascertain the age of serpentinization relative to regional folding.

Contacts

Both upper and lower contacts of the east limb of the folded sill shown in Figure 3 were observed in the field. The sill is underlain by volcanic rocks and the transition from volcanic to ultrabasic rocks seems remarkably gradational in outcrop. The colour of both the fresh and weathered surfaces also seems gradational through a faintly schistose zone from volcanic to ultrabasic rocks. Better criteria for distinguishing the exact contact are based on thin section and chemical data. A much sharper contact was observed at the top of the sill, where within a few inches a coarse-grained tremolite zone grades into a medium-grained meta-gabbro, the latter containing numerous altered feldspar laths.

Fractures

Fractures, most of which are apparently tensional in nature, are common throughout the sills. They are generally filled with one of the following minerals: serpentine (serpophite, chrysotile), tremolite, magnetite. The serpentine is usually fibrous and may form an acute angle with the walls of the fracture, in which case it resembles slickensides. Cross-fibre serpentine is common and a few narrow veinlets of golden-coloured brittle mineral occur here and there. Magnetite is probably the most common fracture filling. It has in places a mammillary structure, but more commonly has a fibre-like, columnar structure standing at right angles to the walls. Colourless tremolite needles also lie along fracture planes and have their axes oriented at an acute angle (20 degrees) to the walls. Magnetite associated with such tremolite occurs as flat ovate patches about 2 cm long and 1 cm wide.

The strike and plunge of forty-four slickenside lineations on fracture surfaces were measured and plotted on a sterionet. These form a girdle whose azimuth is about 45 degrees.

Talc-Carbonate-Chlorite Zones

Parts of the peridotite have undergone alteration to talc-carbonate-chlorite zones; one such alteration zone is shown in Figure 3. The area of more complete alteration is along the nose of the major anticline. As indicated in the figure the alteration transects all the zones of the sills previously described, converting them into a similar rock type. Within this zone of alteration the rock is usually schistose, with some zones exhibiting a particularly intense schistosity. The latter are indicated in Figure 3 as faults. Although the schistosity stands almost vertically, some of the more intensely altered parts of the sill occur as fairly flat-lying layers.

In outcrop the alteration zones are talcose white, pale green, or blue schist with knots of rust-coloured carbonate weathering in relief. The carbonate knots are as much as 2 cm in diameter and are evenly distributed or concentrated either along planes of schistosity or along earlier (?) curving joint planes. Here and there, alteration clearly worked outward from replacement veins. The veins are composed of rusty carbonate (breunnerite, $MgCO_3$ = 13.5 wt. per cent) and quartz, bordered by a half-inch layer of chlorite (Pl. II). This chlorite is more than 16 per cent Al_2O_3 and 15 per cent FeO, and has the following optical characteristics: $N_\beta = 1.606$, optical sign (+). Locally, the carbonate and quartz have a columnar structure, at right angles to the veins, that seems similar to a structure described by Foslie (1931). The schist alongside the chlorite is high in carbonate and chlorite and low in talc, and is more resistant to weathering than the more talcose rock slightly farther away. The schists contain a few small pyrite crystals.

111824

Plate II. *Carbonate-quartz vein (carbonate dark) in carbonate-talc-chlorite rock. The vein has a sheath of almost pure chlorite.*

Although the rock within the talc-carbonate zone is generally schistose, it has not been the locus of any important movement (Fig. 3).

The areal distribution of the talc-carbonate zone cutting across from the base to the top of the peridotite indicates that carbonate and silica metasomatism, which produced first a carbonate-talc-chlorite rock and later a carbonate-quartz-chlorite rock, is a phenomenon that occurs later than the initial serpentinization, and thus is unrelated to it.

The horizontal zones of more intense alteration and localization of alteration on the crest of the structure indicate that movement of material was controlled by primary 'S' planes, which on the nose of the anticline were almost flat lying, and by the major fold structure. These structural controls suggest that alteration was contemporaneous with, or possibly later than, folding. These conclusions are supported by the evidence of intense carbonatization along a major fault zone farther east.

The carbonate-quartz veins were formed by the introduction of CO_2 along structural openings. Silica was probably extracted from the country rock and Cr^{3+}, Al^{3+}, and possibly Fe^{3+} were expelled to form the chlorite borders. It is noteworthy that talc did not form either in the veins or in the country rock directly adjacent to them.

Mineralogy

Olivine

The Quebec-Labrador ultrabasic rocks were originally composed of between 50 and 60 per cent olivine, as indicated by the abundance of serpentine pseudomorphs. This olivine is now indicated mainly by serpentine and tremolite pseudomorphs and /or the distribution of secondary magnetite, but was once in the form of discrete, euhedral or subrounded crystals averaging three quarters of a millimetre in length and about half this in width. These crystals did not show mutually interfering or interlocking relationships, nor do olivine remnants within the pseudomorphs typically show traces of incipient shearing such as translation lamellae or undulose extinction. The only instance of undulose extinction in olivine that was observed was in a section from an intrusive rock in the metamorphic terrain to the east of the Doublet rocks. This rock contains numerous closely spaced, irregular tremolite-chlorite schist planes, indicative of late shearing.

Grains of olivine in the peridotite that were separated from the matrix were found to be megascopically colourless, indicating a low ferric iron content. The β indices of olivines from specimens 7 and 11 (Fig. 3) were found to be almost identical, 1.684 ± .002. The maximum possible variation of these two indices was 0.004, corresponding to about 2 per cent in composition. As these specimens are from localities about 3,000 feet apart and the ultrabasic sill outcrops over a width of only 6,200 feet it is likely that the composition of the olivine is constant throughout the sill. The olivine in a sample from the west limb of the anticline (Fig. 3) and in one other sample from the sill, gave similar indices. The β indices of olivine grains from two small ultrabasic bodies 15 and 20 miles to the east gave values of 1.680 ± .002 and 1.684 ± .002 respectively. Thus no distinct variation in olivine composition has been found in the area. All specimens probably lie between the limits 13.5 and 15 per cent of the fayalite molecule, and therefore fall in the chrysolite group (10 to 30% fayalite) of Wager and Deer (1939). Geochemically, the most abundant olivines are hyalosiderites (30 to 50% fayalite), which are characteristic of "metasomatic ultrabasic rocks, some diabase and basic rocks showing extreme differentiation" (Rankama, 1950, p. 150). The olivines in the 'primary' ultrabasic rocks, e.g., the dunites, average about 10 per cent fayalite (Hess, 1938).

Although within single thin sections the olivines appear relatively constant in size, they have a significant variation in size throughout each sill and between different ultrabasic bodies in the area. Rock specimens from near the floor of the large Griffis Lake ultrabasic sill (Figs. 2 and 3) exhibit pseudomorphs after olivine that are about half the size of those near the central zone, and the pseudomorphs after olivine in the small intrusive bodies to the east are larger than those in the larger ultrabasic intrusions. No evidence was found in any of the ultrabasic rocks of a second generation of olivine lying within the interstices between the larger original grains.

There is no pronounced variation in shape of the olivine pseudomorphs throughout the sill. In most sections most grains appear to have a high sphericity and often a high roundness. The smaller pseudomorphs from near the base of the sills appear to be somewhat rounder than those in the remainder of the sill. About 10 per cent of the olivine crystals had a markedly tabular shape (Pl. III).

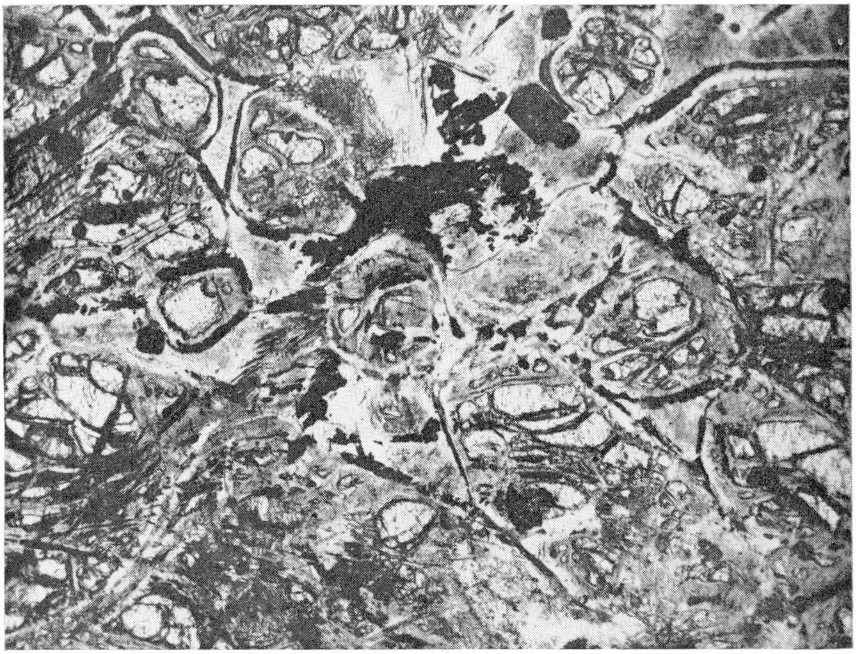

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Plate III. *Partly serpentinized peridotite from the centre of the Griffis Lake sill. Two generations of serpentine are visible. The earlier forms colourless rims partly outlining former olivine grain boundaries, the later consists of yellow patches surrounding the olivine remnants (x25). Plane light.*

Pyroxene

Pyroxene is the only mineral, other than olivine, known to have had a primary (i.e., magmatic) origin in these rocks. It is present in the central part of the sill, between the levels represented by specimens 5 and 12 (Fig. 3). Above and below these levels its place is taken by serpentine (chlorite), ferrotremolite, and actinolite. Pyroxene remnants now comprise from 15 to 20 per cent of the thin section slides, but originally much more was probably present. The pyroxene is present entirely as 0.5 to 1 cm anhedral, interlocking crystals. All are poikilitic, enclosing pseudomorphs after olivine, and less commonly olivine itself.

The optic angle 2V of pyroxene from thirty-one specimens occurring throughout the sills was determined with an universal stage. Slightly different values were obtained from pyroxene grains in the same slides, in some specimens the variation being up to 2 degrees. For any single pyroxene grain and with any one setting of the diaphragm, repeated measurements give constant values for 2V. However, in measuring most pyroxenes, which are generally somewhat altered, the technique of stopping down the light cannot be consistently followed, so that some variable and possibly inaccurate results were obtained. All measurements lie between 50 and 55 degrees; most of them are about 51 degrees. There is no regular variation in the 2V with position in the sill, which suggests that the optic angle and composition of the pyroxene is constant, or relatively so, throughout the sill. Concentrates of pyroxene from localities 5 and 12 (Fig. 3) gave N_β values of 1.684 ± .002 and 1.680 ± .002 respectively, which corresponds to a very minor variation in composition. The β index appears to be slightly higher for pyroxene in the upper part of the sill. The average optics of the pyroxene are summarized as:

Colourless or very faintly coloured in thin section.

Sign (+)
$2V = 52° \pm 2°$
$N_\beta = 1.684 \pm .004$
$Z\Lambda C = 42° \pm 2°$
Twinning—absent

These properties correspond most closely with the composition (Winchell, 1951, p. 410).

$Mg_2Si_2O_6$—46%
$Ca\ Mg\ Si_2O_6$—43%
$Fe_2\ Si_2O_6$—11%

As considerable $Al_2Al_2O_6$ is also present, the pyroxene is a diopsidic augite.

The pyroxene altered initially to a pleochroic brown amphibole and later to actinolite and serpentine. Bastite is not a common type of alteration. Where observed near the base of the sill it is pale green and pleochroic, like more common aluminous chlorite, but it has the characteristic interference colours of serpentine.

The following conclusions were reached regarding the pyroxene in the ultrabasic sill in the area: (1) the composition (diopsidic augite) and abundance (estimated at 20 to 30 per cent) of pyroxene were probably constant or nearly so throughout the sill; (2) pyroxene is decidedly more resistant to serpentinization than olivine, as it is present both above and below the levels at which the olivine is completely serpentinized; and (3) the pyroxene crystals appear to have grown in place, as individual crystals interlock and lack twinning or any other evidence of pervasive shearing.

Chlorite Minerals

Three contrasting types of chlorite minerals have been recognized in the ultrabasic rocks in the area.

The first of these appears to be typical serpentine. It occurs characteristically in veinlets crossing olivine grains or replacing the outer borders of grains. In these occurrences it has a fibrous habit, the fibres standing at right angles to the surface of growth and having parallel extinction. Where it replaces pyroxene or lies in interstices between grains it is generally blade-like in form. The characteristic feature of this serpentine is a pale blue, slightly anomalous interference colour, rarely grading into yellow. The average index as measured on grains from sample 6 (Fig. 3) is 1.572 ± .002. In plane light this serpentine is characteristically colourless or very pale greenish.

A later serpentine replacement of olivine and in places of tremolite has a similar habit and occurrence. It is, however, strongly yellow and is the latest mineral in rock that has not undergone CO_2 metasomatism. The birefringence of this mineral and its indices are masked by the colour, but here and there veinlets of fibrous yellow character showing high first order birefringence occur. These show a strong colour banding (yellow) parallel to the vein walls, intense pleochroism, and a birefringence up to first order blue. The birefringence is a function of colour—hence probably of the iron content. This serpentine is the ferriferous chrysotile—xylotile. Two serpentines, the later more iron rich than the earlier, suggest a break in the process of serpentinization similar to that described by numerous writers. The yellow serpentine in these rocks is the youngest mineral, replacing even tremolite.

The replacement of individual olivines by serpentine was carried out on a volume for volume basis as evidenced by the complete replacement of olivine poikilitically enclosed in unaltered, unfractured pyroxene. Furthermore, there is no evidence that such poikilitically enclosed olivines are any more or less altered than those not thus enclosed. The largest amount of remnant olivine in any slide would not exceed 10 per cent, and only 3 or 4 per cent of the 'central zone' is now composed of the mineral.

The serpentinization of the succeeding zones in general appears similar to that which occurred near the centres of the sills. However, some thin sections of specimens from the intensely serpentinized intermediate zone show a conversion of chrysotile to bladed antigorite. The antigorite appears as unoriented daggers and has a pale yellow interference colour. These blades of antigorite probably mark zones of slight shearing, although there is no megascopic evidence of this.

Serpentine, characterized by a lack of colour in plane polarized light and pale blue interference colours in doubly polarized light, decreases progressively outward from the intermediate serpentine zone into the outer, tremolitized zone. At levels represented by specimens 3, 4, 14, 15 (Fig. 3) the serpentine occurs only as pseudomorphs after olivine. As such it is fibrous, forming an outer rim and cross-cutting fractures in the former olivine grains. Many of the centres of the pseudomorphs are filled with unoriented tremolite needles and the interstices between pseudomorphs are filled by faintly green, almost isotropic, fine-grained chlorite, whose average index is 1.580 ± .002. In the lowest (specimen 16, Fig. 3) and uppermost levels of the sill, serpentine is wholly unstable and its place is taken by chlorite and actinolite.

Chrysotile (mesh serpentine) and unaltered olivine lenses lie in a schistose matrix of chlorite and tremolite in the small ultrabasic bodies lying within the metamorphic terrain to the east.

Garnierite has been observed in thin sections showing ferric iron serpentine (xylotile) in the central, relatively unserpentinized zone of the main ultrabasic sill. It occurs between olivine crystals and is finely crystalline, apple green in plane polarized light (faintly pleochroic) and almost isotropic (purplish blue). The ferric state of the iron gives a yellow colour to the xylotile and reflects the high redox potential existing at the time of its formation, which, in turn, probably indicates the superficial conditions under which both minerals formed. Spectrochemical analyses show no concentration of Ni in the sill. The nickel in the intermediate zone of the sill, where complete serpentinization took place because of higher temperature and reducing conditions, probably entered the chrysotile lattice and so did not form a separate nickel-rich silicate mineral.

The two generations of serpentine in the central zone of the sill, indicate clearly that H_2O was introduced in two stages in the history of the alteration of the ultrabasic rocks. The different colour of the second serpentine (xylotile) indicates a change in partial pressure of oxygen during the second stage of alteration. This ferric iron serpentine (possibly with a higher total iron content) will dissolve less Ni than will the normal type of serpentine, hence garnierite was formed.

The fibrous serpentine replacing olivine and a chloritic mineral in the interstices between olivine grains are of some petrologic interest. The minerals are considered to have a slightly different composition, the chloritic mineral in the interstices probably being higher in Al, Fe, and Ca than the fibrous serpentine. Their occurrence together and their contrasting appearances suggest that they represent two stages of alteration. The serpentine is undoubtedly the older and higher temperature alteration. Following development of the serpentine a break occurred in the alteration processes and the chlorite formed at a time when more Al, Fe, Cr, Ca were available. This alteration probably took place in response to relatively low grade regional metamorphism, when small amounts of feldspar in the ultrabasic rocks broke up and the Al from the feldspar became incorporated in the late chlorite.

A strongly pleochroic variety of chlorite is intergrown with magnetite, and probably formed during serpentinization. It may have absorbed some of the trace elements that are unable to enter serpentine or magnetite during serpentinization.

According to Du Rietz (1935), peridotite bodies are less altered in gneissic rocks than they are in sedimentary schists, which condition he ascribed to a lack of water in the gneisses. The highly sheared ultrabasic rocks that outcrop in gneissic terrain towards the eastern border of the Central Labrador Trough are likewise relatively unaltered. The olivine remnants in these rocks cannot be ascribed to a scarcity of channelways for introduced water, as heavily sheared zones are present. The writer agrees in general with Du Rietz's suggestion that the extent of serpentinization may be controlled by the composition of the country rock.

The larger masses of ultrabasic rocks of the Central Labrador Trough are composed primarily of chrysotile and show little or no evidence of shearing. Small masses in the highly metamorphosed terrain to the east are sheared throughout and are now composed of lenses of olivine and chrysotile in a matrix of chlorite and tremolite. The crushed olivines show undulatory extinction and adjacent remnants have been rotated during deformation and extinguish at different angles. The metamorphic grade of the surrounding rocks (amphibolite) is higher than that indicated by the ultrabasic rocks (in part chlorite-tremolite schist). The amphibolite contains dark green hornblende and plagioclase (An_{50}), so was developed before the ultrabasic rocks were sheared.

Amphiboles

Members of the isomorphous series tremolite-actinolite-ferrotremolite are, next to the serpentines, the most common metamorphic minerals in the ultrabasic rocks in the Central Labrador Trough.

The earliest formed member of this group was brown actinolite with the following characteristics:

> Pleochroism strong; α = pale brown or colourless, β = brown (reddish), γ = brown; $2V = 80^{\circ+}$; optically negative; $Z\Lambda C = 18^{\circ}$; $N_{\beta} = 1.668 \pm .004$; $Z-Y = 0.020$

It occurs throughout the sill with the exception of one highly serpentinized zone near the base (specimens 13 and 14, Fig. 3) and is clearly pseudomorphic after pyroxene. The edges of some of the brown amphibole grains grade through a pale green border into colourless tremolite, but the transition is generally sharply and directly into colourless amphibole. Much of the brown amphibole contains subrounded inclusions of tremolite (pseudomorphic after olivine). The optic planes (010) of the brown actinolite and tremolite are generally parallel, but the birefringence and extinction angle are both lower in the ferrotremolite-rich variety. The presence of brown actinolite in thin section is an excellent criterion of the original ultrabasic composition of a particular specimen. This criterion is of particular value because of the ubiquitous occurrence of the brown actinolite in the ultrabasic rocks, which, in turn, attests to its essential stability under a large range of temperatures and compositions. For example, it is found in ultrabasic rocks composed almost entirely of pyroxene and serpentine, and in other ultrabasic rocks from the outer zone, which are composed mostly of actinolite and chlorite. The narrow, gradational pale green zones around the iron-rich variety indicate a change through the stability range of green actinolite to that of tremolite.

Tremolite has a more varied occurrence than the actinolite, being present throughout the sill and particularly abundant in the outer tremolitized zones. Where it is pseudomorphic after pyroxene it forms fairly equidimensional crystals as much as a centimetre in diameter. In parts of the sill originally high in pyroxene (patches near the top of the sill) the tremolite, by replacing pyroxene and by outward growth, may form up to 80 per cent of the rock. The resistance of these tremolite crystals to weathering gives the rocks in the outer zone their characteristic knobby surfaces. Under the microscope, many of the tremolites exhibit a fine polysynthetic twinning.

The tremolitization of the poikilitic pyroxenes is somewhat unusual and is described in detail. Where the alteration is least complete, remnants of olivine lie embedded in fibrous serpentine, which is covered by a thin layer of tremolite (Pl. IV), and are, in turn, enclosed by single large grains of pyroxene. Tremolite also fills minute fractures in the pyroxene. The unique aspect of this texture is that all the tremolite within each pyroxene extinguishes as a unit and its optic plane (010) and crystallographic c axis [001] roughly parallel that of the surrounding pyroxene. Clearly when the entire rock was essentially solid, recrystallization took place involving the pyroxene

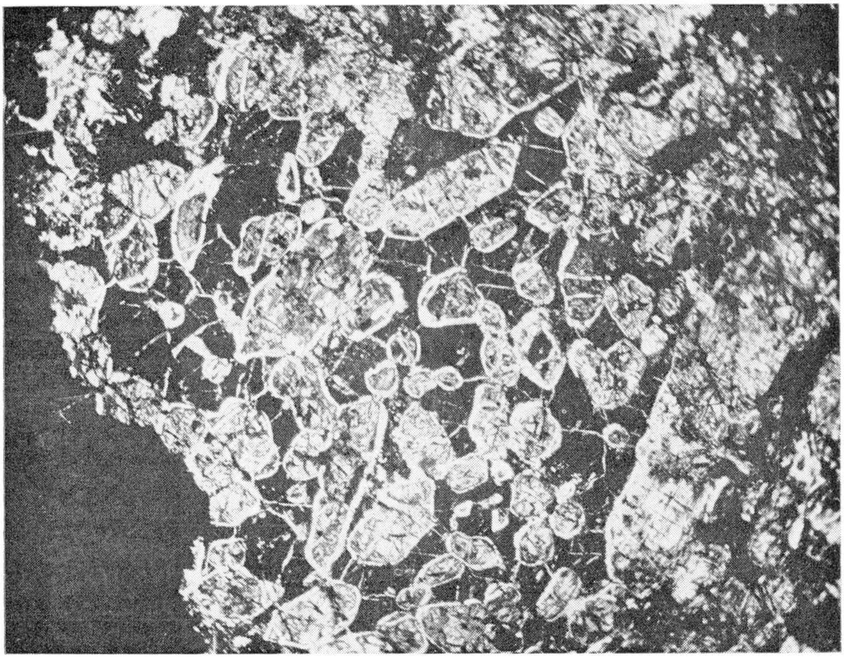

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Plate IV. *A single poikilitic pyroxene containing partly serpentinized olivine grains rimmed by actinolite. The actinolite (white) is optically continuous throughout the pyroxene, which is at extinction here. (x20) Crossed nicols.*

and olivine, and the optic orientation of the resulting tremolite was controlled by the lattice of the surrounding pyroxene. A similar type of texture, but with a somewhat different interpretation, has been reported elsewhere (Hess, 1933). Although colourless amphibole patches (after olivine) may be observed lying in a ferrotremolite matrix (after pyroxene), the presence of pseudomorphs of optically continuous tremolite (after olivine) in a chlorite matrix (after pyroxene) does not necessarily imply an earlier, overall conversion to amphibole as Hess postulated. The extent of metasomatism and the evident ease of migration indicated in these rocks make it particularly unlikely that the slight differences between the composition of the amphibole replacing olivine and that replacing pyroxene would cause the formation of distinctive chlorites as indicated by Hess (1933). The sequence suggested by Hess and modified by the writer is illustrated in Figure 4.

The reaction is represented as follows by the writer:

$$\underset{304.2\ \text{cc}}{Ca_4Mg_5Fe(SiO_3)_{10}} + \underset{142\ \text{cc}}{5/17\ Mg_{17}Fe_3(SiO_4)_{10}} + \underset{68\ \text{cc}}{{}_3SiO_2} + \underset{36\ \text{cc}}{2HO_2}$$

$$\rightarrow \underset{545\ \text{cc}}{2Ca_2Mg_5Si_8O_{22}(OH)_2} + \underset{25.7\ \text{cc}}{2/3\ Fe_3O_4}$$

diopsidic augite + chrysolite (olivine) + silica + water → tremolite + magnetite

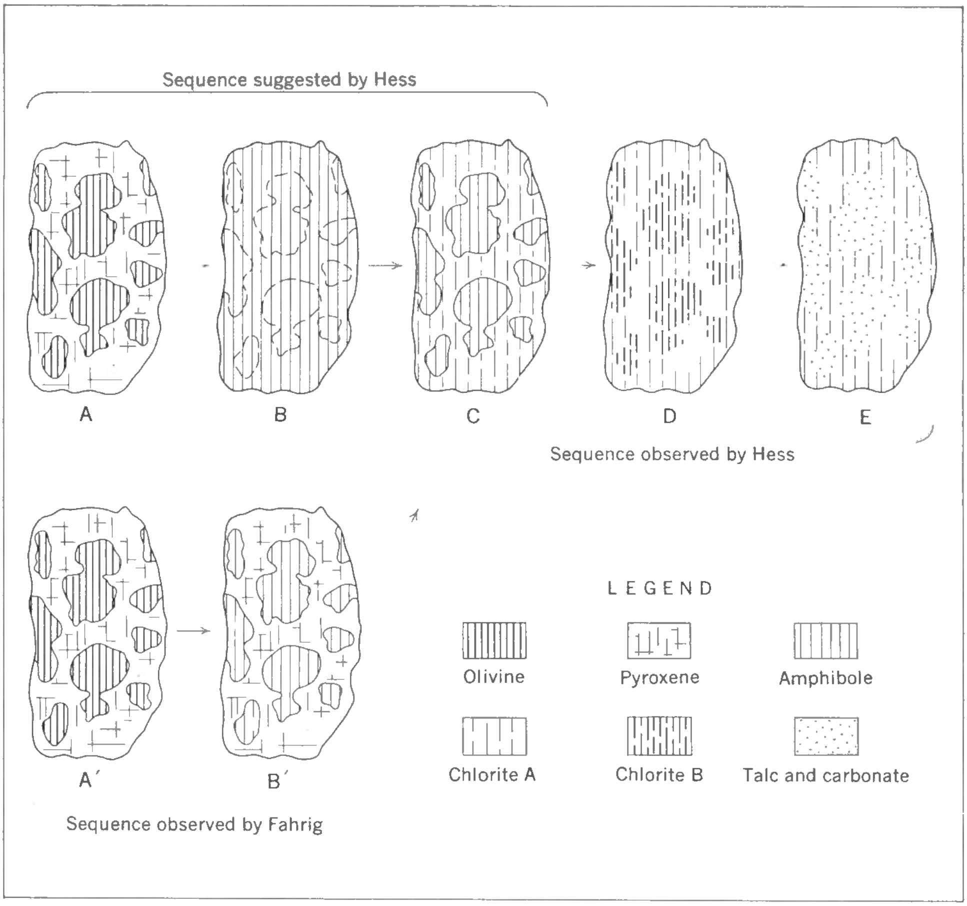

Figure 4. Sequence of alteration of poikilitic pyroxene suggested by Hess, 1933 (upper diagrams). Lower sequence observed by Fahrig.

Then 1 cc of silica and water must be added to 4.33 cc of pyroxene and olivine to give 5.5 cc of tremolite and magnetite. The volume increase in the reaction amounts to 28 per cent, and the reaction is exothermic.

The indices of refraction of the colourless amphibole indicate a composition of between 10 to 20 per cent ferrotremolite molecule. There are probably all gradations in composition between this and the 40 per cent ferrotremolite of the brown amphibole, but most of the amphiboles fall in either one group or the other. This indicates an essential difference in conditions existing during their formation—i.e., the brown amphibole (40 per cent ferrotremolite) possibly being of magmatic origin, the tremolite (10 to 20 per cent) being of metamorphic origin.

Colourless clino-amphibole has a second distinctive pseudomorphic occurrence in the ultrabasic rocks. It replaces large (3 mm), equidimensional poikilitic crystals, which once contained, and in some cases still contain, olivine crystals. The unique feature of this replacement is that the tremolite pseudomorph is composed of a large number of tiny unoriented patches, often with a fibrous structure. Within these pseudomorphs are patches of serpentine, which extinguish as a unit (bastite), and which appear to follow earlier cleavages. The whole mass, bastite and tremolite, may originally have been a larger pyroxene. The replacement of pyroxene by a felted mass of tremolite instead of by a single crystal may reflect the late nature of this type of alteration, or might indicate the former presence of a second type of pyroxene (orthopyroxene?).

The colourless amphibole also occurs as individual needles scattered throughout the groundmass and as unoriented grains in the centres of what once were olivine crystals. The olivine pseudomorphs have a border of fibrous serpentine and a core of unoriented tremolite needles. This texture occurs only in the outer zone.

Colourless amphibole is common in the sheared ultrabasic bodies near the eastern border of the map-area. Typically the rock there is composed of lenses of mesh serpentine, with or without olivine remnants, lying in a highly schistose matrix of chlorite, tremolite, and magnetite. The tremolite within these layers has a preferred orientation, so the irregular parting planes of the schist exhibit a strong amphibole lineation. The chlorite present has a low 2V and $N_\beta = 1.580$.

In summary, there are two main amphiboles in the ultrabasic sills—a pleochroic brown actinolite and an almost colourless tremolite. The pronounced difference in their optical characteristics suggests a sharp break in the physical conditions of their formation and hence a late magmatic origin for one (ferrotremolite), and a metamorphic origin for the other (tremolite). Where formed by alteration of pyroxene or formed by reaction next to pyroxene, the orientation of the tremolite is controlled by the lattice of the pyroxene. The tremolite grains have (010) and [001] roughly parallel to that of the enclosing pyroxene and thus the original pyroxene fabric might conceivably be determined by measurement of the fabric of the secondary tremolite.

GEOCHEMISTRY

The Bulk Chemical Composition

It is essential in discussing the petrology of the ultrabasic rocks that their present bulk chemical composition as well as the details of chemical variation should be considered. The bulk composition of such bodies is seldom determined, for only 'representative samples' are analyzed. As most such rocks are highly metasomatized, it is desirable to sample them in a more systematic manner.

A bulk sample was therefore prepared from samples 3 to 16 (Fig. 3), collected from the base to the top of the sill. These specimens were finely ground and carefully split, and a composite sample was prepared from them. The writer believes that the analysis of this sample represents closely the present bulk composition of the Labrador ultrabasic rocks. The outer tremolitized zones may be over represented, but this may be corrected from the spectrochemical analyses. The chemical analysis is given below (Table III). For comparison, the average compositions of 'primary ultrabasic rocks' from Massachusetts, Finland, Newfoundland, Southern Rhodesia, and Cuba (Hess, 1938), are also shown in Table III.

Table III

Analysis of Labrador Ultrabasic Rocks Compared with Average Given by Hess (1938)

	Average by Hess (1938)	Composite Sample* Griffis Lake sill, Labrador
SiO_2	39.48	38.65
Al_2O_3	1.44	6.59
Fe_2O_3	5.84	4.24
FeO	2.73	6.93
MgO	37.60	29.74
CaO	0.35	3.52
Na_2O	0.23	0.15
K_2O	0.11	0.10
P_2O_5		0.06
H_2O+	11.48	8.35
H_2O-	0.67	0.24
Cr_2O_3	0.38	0.08
NiO	0.17	0.14
MnO		0.16
CO_2		0.59
TiO_2		0.34
S		0.21

* Analyst: H. B. Wiik, Helsinki, Finland.

According to Hess (1938), the features of the 'primary ultramafic magma series' that set them apart from other ultrabasic rocks are:

1. Molecular ratio – $\frac{Mg}{Fe} = 7.5$ for peridotites, dunites, and serpentinites
   $= 6$ to 7 for pyroxenites
2. Low in CaO and Al_2O_3, as well as alkalis and TiO_2.

Chromium-Nickel Ratio in the Bulk Sample and its Significance

Comparative figures for the chromium and nickel content of peridotite in the Labrador Trough and of various other rock types reported by others are given in Table IV. As can be seen from this table, in almost every example of diorite, gabbro, pyroxenite, and peridotite (or their serpentinized equivalents), the Cr_2O_3 content is considerably higher than the NiO content.

Table IV

Comparison of Chromium and Nickel Content of Various Rock Types

—	Cr_2O_3 ppm	NiO ppm	
Peridotite	3400	3160	Averages by Goldschmidt (1937)
Gabbro	340	158	
Diorite	68	40	
Granite	2	2.4	
Nepheline syenite	0.7	2.4	
Ultrabasic rocks	3800	1700	Average— H. H. Hess (1938)
Gabbro picrite	1500	1000	Wager and Mitchell (1948)
Eucrite	300	350	
Olivine gabbro	230	120	
Middle gabbro			
Peridotite	800	1400	Quebec-Labrador *see* Table III

In the Labrador ultrabasic rocks the reverse is true, for NiO is almost twice as abundant in the bulk sample as Cr_2O_3. This phenomenon may be explained by the high olivine content (about 60 per cent by volume) of the Labrador peridotite, and the absence or near absence of primary chromite and magnetite. Wager and Mitchell (1948) have shown that in an extreme differentiate of basic magma, such as the Skaergaard Intrusion, little or no chromium will enter the olivine lattice, whereas nickel enters the olivine lattice quite readily. The low ferric iron content of the olivine in the Labrador ultrabasic rocks indicates reducing conditions during crystallization.

The $NiO-Cr_2O_3$ ratio of the bulk sample of the Labrador peridotite provides strong evidence that this ultrabasic rock resulted from the extreme differentiation of a basic magma.

Variation in Minor Constituents Throughout the Ultrabasic Sills

Chemical Data

In order to determine how the composition of the ultrabasic rocks varies throughout the sill, semiquantitative spectrochemical analyses[1] were made for most of the minor constituents. The position of these specimens within the sill is shown on Figure 3, and the analytical data are shown in Figure 5. These data are simply plotted against the position of the specimens in the sill.

Although the values obtained for each element are only approximately correct, the variation in the amounts of each element is accurately indicated. This is true because the matrix material for all the specimens, with the exception of the three gabbros, is similar. The standardization problem in determining minor elements spectrographically from two specimens of widely different composition does not then arise. A check on the reproducibility of the results is also available. Five specimens, collected and submitted for analysis a year previous to the present work, gave similar relative amounts of minor elements. Furthermore, as an accurate composite specimen was prepared and completely analyzed, it can serve as a standard for determining the oxide percentage of each minor element from any of the individual samples. Such calculations then enable us to compare the composition of any of these specimens with that of any other ultrabasic rock in the usual terms of oxide percentage.

It is clear from the data presented in graphical form (Fig. 5) that the border zones of the ultrabasic sills exhibit variations in minor constituents, which set them off from the main bulk of the intrusion. Aluminum is greater in these border zones by a factor of about ten, calcium by a factor of about two, and titanium by a factor of about three. Iron doubles towards the upper and lower contacts, but also shows a consistent decrease from the base upward in the sill. Sodium, manganese, chromium, and nickel either are constant throughout the sill or show minor fluctuations.

General Discussion of Chemical Variation

There are only two ways in which an originally homogeneous intrusive rock may develop parts of contrasting chemical characteristics. These are by differentiation of the intrusive body (magmatic or metamorphic) and by the differential introduction of material. The first is an internal process, and with an intrusive mass of given composition the trend of the process is affected mainly by the temperature and pressure of the environment and by shearing. The second involves mechanisms that are more complex and are dependent also on the chemical character of the surrounding rocks.

The splitting of an originally homogeneous rock into parts of varying chemical composition may be accomplished in the liquid state (crystal fractionation, diffusion)

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[1] Prepared by the Spectrographic Laboratory, Mines Branch, Ottawa.

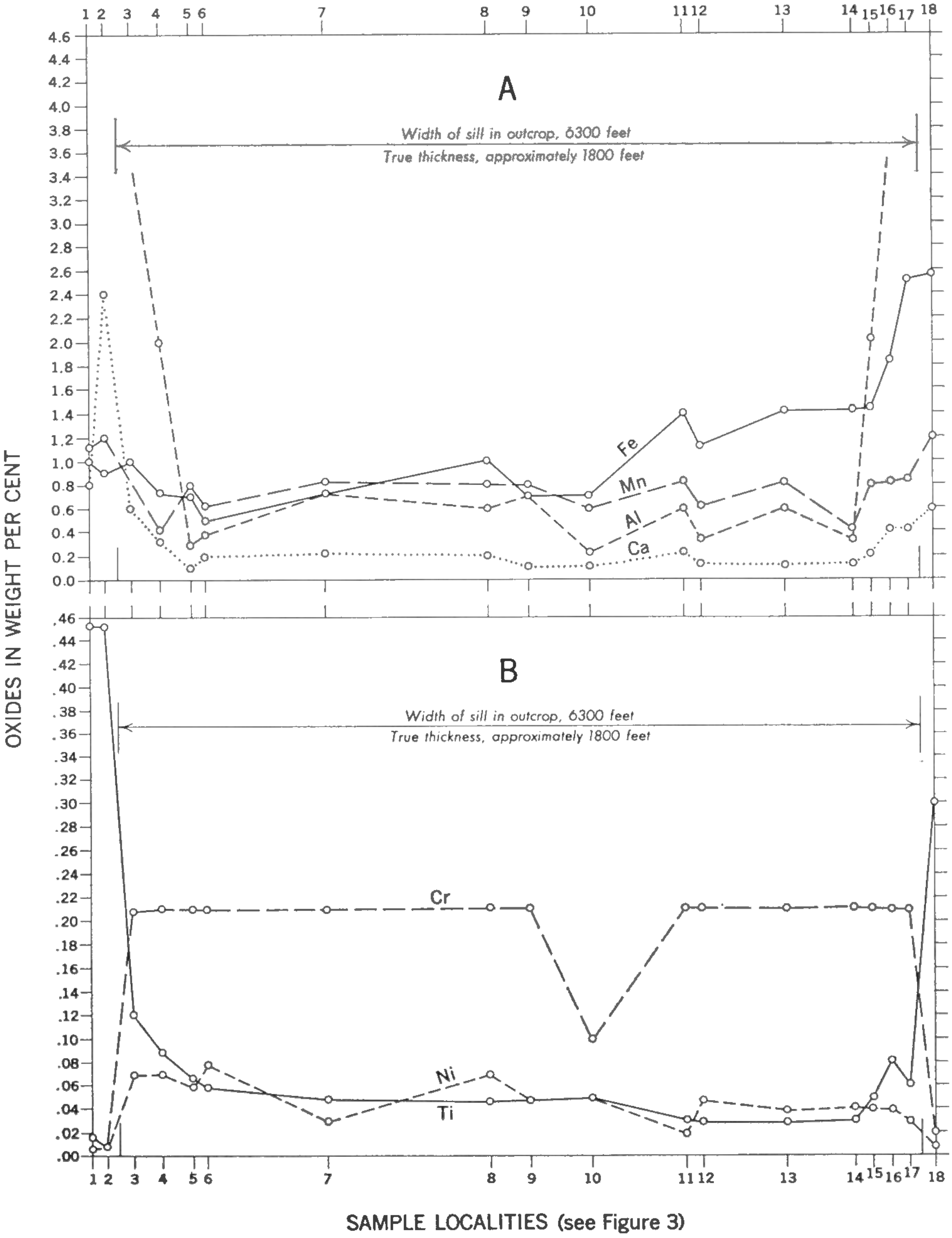

Figure 5. *Chemical variations within the Griffis Lake ultrabasic sill; A, variation of the Fe, Mn, Al, and Ca; B, variation of the Cr, Ni, and Ti.*

or in the solid state (metamorphic differentiation). Aside from the possibility of a chilled contact phase, crystal fractionation generally requires that there be a regular and consistent variation in the amount of certain elements from the base towards the top of a fractionally differentiated body. Thus, such a process is ruled out for the Labrador ultrabasic rocks because of the constancy of most of the elements throughout the central part of the sill, where fractional crystallization should have been most active. This conclusion is further substantiated by the constancy of the composition of the olivine and pyroxene remnants.

A second possibility for differentiation in the liquid stage is by thermo-diffusion (thermal diffusion and convection), a mechanism that has been suggested to explain a layered ultrabasic complex of Blashke Island, Alaska (M. S. Walton, 1951). Walton's explanation depends much on the outward migration of volatile fluids, including lime and silica, for convection is unlikely to have been strong. But Bowen (1949) has pointed out that it is unlikely that more than a minute amount of magmatic volatiles would be present to bring about fairly large scale outward diffusion, such as would be required in the Labrador Trough area.

If migration took place during a magmatic stage, it should affect those elements most strongly concentrated in the liquid phase. Chromium shunned early olivine and entered into the pyroxene phase in the Skaergaard Intrusion (Wager and Mitchell, 1948), but this element is most constant in the present study. Ni, on the other hand, should be concentrated in the olivine structure, particularly since the pyroxene is calcic, but even it varies widely, and we must conclude that this is a later metamorphic effect probably occurring during the period of serpentinization.

Discussion of Chemical Data in Terms of Semi-solid Intrusion

When a fluid is forced to migrate under ordinary circumstances, differential movement occurs within the mass and hypothetical shear surfaces are set up. If the fluid mass is sheet-like in form and if the confining surfaces are smooth in comparison to the thickness of the sheet, these shear surfaces will be planar and will lie parallel to the confining walls. The spacing of the resulting flow layers will be a function of the distance of a point from the confining walls and the fluidity of the mass. That is to say, as the walls of an intrusive sheet are approached the distance between flow units should decrease. Fluidity is a function of the chemical composition of the fluid, the temperature, and the pressure, plus the character and amount of any suspended solid phase. A suspended solid phase will increase viscosity because the friction between solid and fluid is greater than that between fluid and fluid, and, of course the friction between solid and solid is generally greater than that between fluid and fluid.

Let us assume that confining walls are relatively smooth, that the fluid phase is liquid of low viscosity, and that 'suspended' within it are tabular, solid particles that form approximately 60 per cent of the mass. In order that such a mass migrate by laminar flow, the spacing of potential flow layers must be greater than the average thickness of the suspended particles. If the shearing is intense near the upper and lower contacts, then each tablet will tend to move relative to its neighbours above and below. If the coefficient of friction is relatively high this penetrative movement will result in some 'turbulent' flow in the upper and lower parts of the sheet. Laminae flow units will form towards the centre, and within each unit, where very little shearing movement takes place, the tablets will lie parallel to the confining shear surfaces. The result of this difference in shearing in the central and outer part of a sheet will result in closer packing towards the central part and a lower packing towards the outer parts. In essence this means a flow of liquid towards the upper and lower contacts, where more fluidity is required by the mechanism of flow. If the liquid and solid particles are not of the same composition, then the result is a chemical differentiation. Furthermore, near the upper and lower contacts the solid particles should be rapidly rounded off and their average size decreased. This is found to be true in the ultrabasic rocks of Quebec-Labrador. In these rocks the percentage of olivine (now replaced) was certainly less towards the boundaries of the sills, the average grain size of the olivine was considerably less near the boundaries than towards the centres of the sills, and crystals were decidedly more round. Plate I shows a joint pattern, which probably indicates the thickness of the flow layers originally present towards the central parts of the sill.

If the above mechanism was operative in the ultrabasic sill (Fig. 3) and the variation at the upper and lower contacts was a result of the flow of liquid (decrease of solid phase) towards the boundaries, then a higher concentration of certain elements would be expected in these zones (each about 370 feet wide). Since the postulated liquid would have had a composition of pyroxene plus calcic plagioclase, Al, Ca, and Ti should all increase towards the borders. Mn would stay about constant and Ni and Fe would probably decrease. With the exception of Ni and Fe such is indeed the case.

However, that Fe did not, in fact, decrease can be fairly easily explained because of the additional chemical differentiation caused by serpentinization. As shown by the spectrochemical analyses and as indicated by field observations, the Fe of these rocks appears to have been a highly mobile substance. Moreover, the writer believes its migration is an essential part of the process of serpentinization. As shown on Figure 5, Fe appears to be concentrated towards the base of the ultrabasic sill, and to a lesser extent towards the top. These concentrations are proportional to the extent of serpentinization, as the wider zone of serpentine is towards the base.

According to Korzhinsky (1948), the mobility of iron is strongly controlled by temperature, it being mobile during the high temperature formation of andradite skarns and contact magnetite rocks. If this is true then the temperature at which these ultrabasic rocks were altered must have been relatively high.

Distribution of Minor and Trace Elements During Serpentinization and Steatitization

It is interesting to compare the behaviour of cobalt and nickel during the processes of serpentinization and steatitization (*see* Table V). These elements act in a similar manner during sepentinization, both being enriched in the magnetite phase. Cobalt, however, has a magnetite-serpentine distribution ratio of 6 compared to 3 for nickel. The ionic radii of these elements are so close that one suspects that size is not the determining factor in this distribution. The two elements behave in a strikingly different

Table V

Distribution of Minor and Trace Elements in Coexisting Metamorphic Minerals During Serpentinization and Steatitization[1]

Elements	Average Wt. % of Elements as Oxides	
	Olivine (60% of Original Rock)	Pyroxene (20% of Original Rock)

Part A. Primary Minerals

Elements	Olivine (60% of Original Rock)	Pyroxene (20% of Original Rock)
Cr	0.07	0.29
Ni	0.21	?
Co	0.02	0.02
Mn	0.23	?
V	0.004	0.01
Ca	0.35	High
Al	0.43	?
Metallic Fe	12.2	…

Part B. Serpentinization

—	Magnetite	Vein Magnetite	Serpentine	Actinolite	Distribution Ratios		
					Magnetite	Serpentine	Actinolite
Cr	0.81	Low	0.13	0.29	6.2	1	2.2
Ni	0.51	0.09	0.17	0.12	3	1	0.70
Co	0.08	0.015	0.013	?	6.2	1	?
Mn	High	0.05	0.10	0.10	?	1	1
V	0.045	Low	0.01	0.013	4.5	1	1.3
Ca	?	?	0.65	High	…	…	…
Metallic Fe	High	High	6.2	4.8	H	1	0.77
Al	1.12	0.07	3.1	4.5	36	1	1.45
Ti	0.11	0.04	…	…	…	…	…

Part C. Steatitization

—	Talc	Carbonate	Chlorite	Distribution Ratios		
				Talc	Carbonate	Chlorite
Cr	0.16	0.02	0.94	0.17	0.02	1
Ni	0.23	0.07	0.24	0.93	0.3	1
Co	0.006	Low	Low	…	…	…
Mn	Low	0.37	0.068	Low	5.4	1
V	0.006	Low	0.03	0.2	Low	1
Ca	0.20	0.25	0.23	0.87	1.1	1
Metallic Fe	0.43	17.	11.0	0.40	1.5	1
Al	1.10	0.44	High	2.5	1	H

[1] Quantitative spectrographic analyses by W. Fahrig.

way during steatitization (CO_2 metasomatism). Nickel is high in coexisting talc and chlorite, low in carbonate, whereas cobalt is low in all three phases (probably less than 60 ppm). Cobalt apparently leaves the system entirely during this type of alteration, possibly as a bicarbonate solution. A considerable separation of nickel and cobalt thus results during this type of metamorphism. Nickel and cobalt are both reduced by a factor of 5 in vein magnetite that is produced during serpentinization, indicating similar mobility during this stage of alteration.

Chromium is strongly concentrated in secondary magnetite but has extremely low mobility during this stage of alteration. The chromium content of vein magnetite is about 10^{-3} times that in the serpentinite. During steatitization the chromium is strongly concentrated in chlorite (up to 1.2%) and to a lesser extent in talc (0.16%). The fixation of chromium during this stage is probably much dependent on the presence of chlorite. If the rocks were highly deficient in Al^{3+} both Fe^{3+} and Cr^{3+} would probably be forced to migrate. The production of pure talc occurs under such conditions of alteration and the country rock is enriched in Fe^{3+} and Cr^{3+}.

STRUCTURAL PETROLOGY

Petrofabric Data

Optic directions α and γ of 136 olivine grains in a thin section of a specimen taken from the relatively unserpentinized central zone of the main peridotite sill are shown in Figure 6. In outcrop this zone showed the characteristic black colour and strong 'S' plane development parallel with the walls of the sill. The rock tends to split along these 'S' planes. Two less conspicuous joint planes lie at about right angles to this, the more prominent of which includes the dip line. A prominent dimensional orientation is visible under the microscope. Contours determined were for 0, 1, 2, 3, 4 points per unit area. The maximum concentration in one per cent of the area was 6 points, that is, about 5 per cent. Figure 6a shows the plot of 136 α directions, which form a polar concentration and partial girdle. This concentration is rotated 20° to 30° clockwise from the pole to the megascopic 'S' plane, probably because of poor orientation of the thin section. Figure 6b is a plot of γ, which shows a fairly strong concentration at right angles to the maximum. All olivine grains in the thin section were plotted with the exception of those lying within pyroxene. A separate plot was made for the α direction of thirty-four olivine grains lying within pyroxene in this thin section. The resulting pattern conformed fairly closely to that of Figure 6a.

A second thin section was prepared from a specimen from the opposing limb of the anticline 7 miles southwest of the original location of the specimen already described. This rock contains no megascopically visible 'S' planes but shows under the microscope a striking dimensional parallelism of magnetite veinlets around the olivines and chrysotile veins within. Microscopic observations also indicated that the smaller olivine crystals are generally less oriented than the larger ones, but this is to be expected, because they commonly lie in protected interstices between larger grains. Figure 7a shows the plot of α and β of the thirty-six largest grains intercepted in traversing the thin section. α shows a strong polar concentration, whereas β forms a girdle. A concentration of β within this girdle is probable. Figure 7b is a similar plot of fifty-one olivine grains lying within large pyroxene grains in the same slide. The concentration coincides with Figure 7a, but may be somewhat less distinct owing to the fact that all grains within the pyroxenes were measured in order to obtain a reasonable number of grain measurements.

Petrofabric studies of the pyroxene in the peridotite sill have also been made. Figure 8a shows the plot of α, β, γ orientation of twenty large poikilitic pyroxenes from the intermediate zone. Three additional thin sections were cut at right angles to the first and forty pyroxene orientations were measured and plotted (Figs. 8b, c). In these figures the plots of the poles β and γ have been rotated into a single plane. They show a slight concentration, but this may well be fortuitous because a single pyroxene of large dimensions whose parts may extinguish at a slightly different angle can easily though erroneously be plotted as two or more grains. The existence of a definite pyroxene fabric has not been proven.

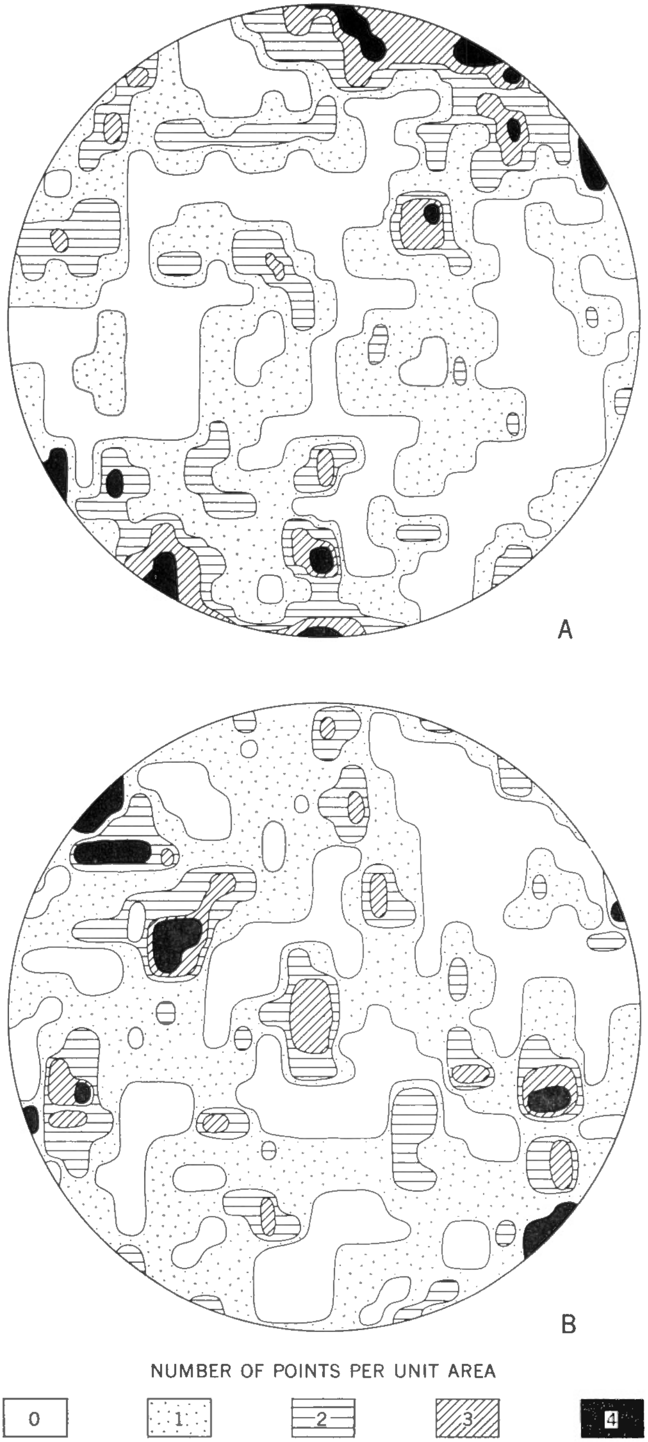

Figure 6. *Diagrams of optic directions of 136 olivine crystals; A, α axis; B, γ axis.*

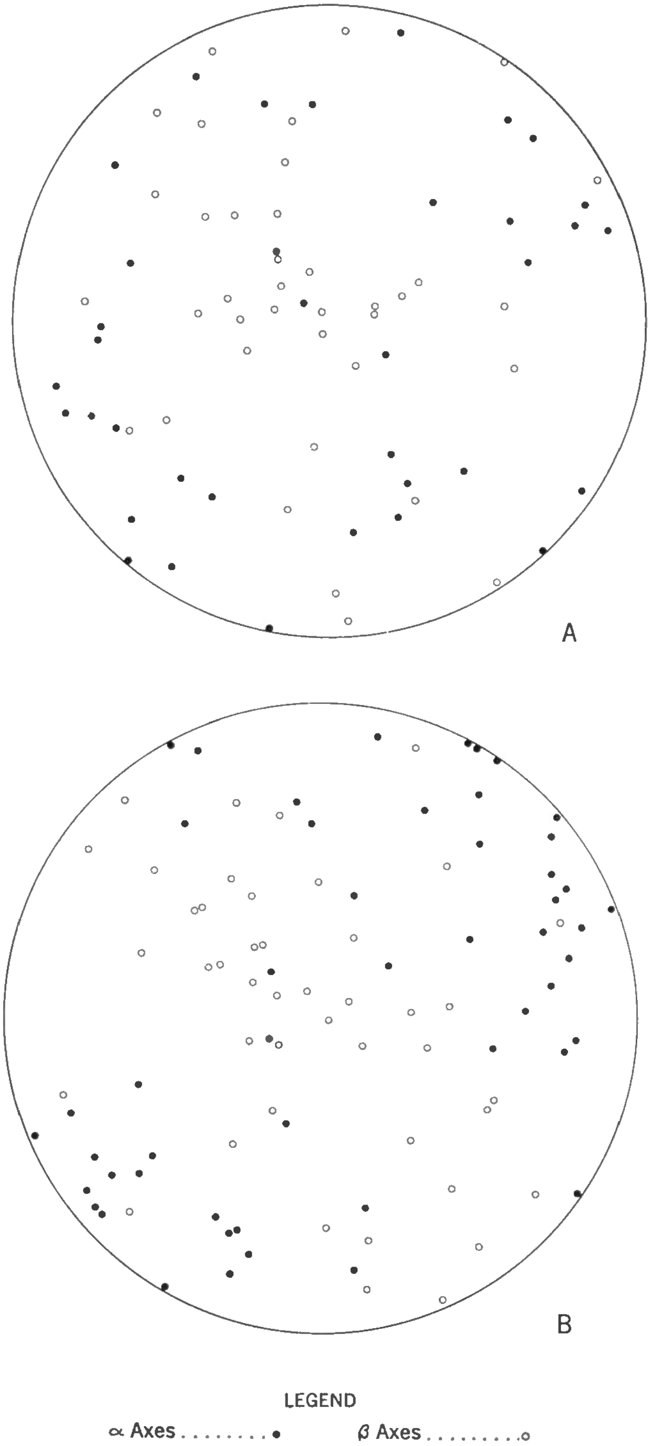

Figure 7. *Diagrams of α and β axes showing strong dimensional orientation. A, thirty-six olivine grains within five poikilitic pyroxene grains; B, fifty-one olivine grains.*

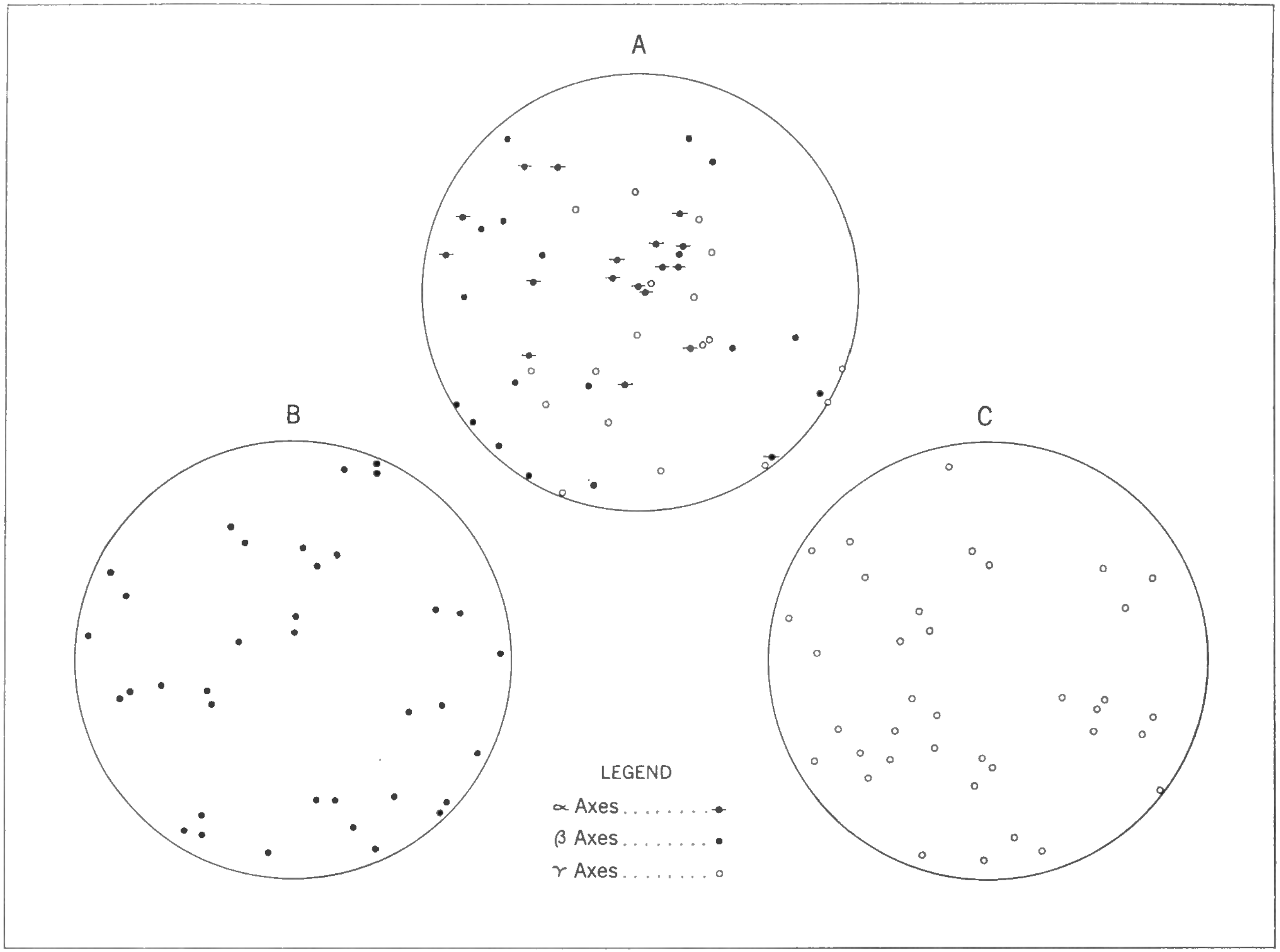

Figure 8. *Diagrams of optic directions of pyroxene grains. A; α, β, and γ axes of twenty large poikilitic grains; B; β axes of forty poikilitic pyroxene grains; C; γ axes of forty poikilitic pyroxene grains.*

The azimuths of the long dimension of 153 olivine granules lying within sixteen pyroxenes in the same thin section were plotted in a rosette diagram (Fig. 9). This diagram indicates a distinct two dimensional orientation of enclosed olivine. The two poikilitic pyroxenes in this slide mesh completely and show no sign of euhedralism.

A second diagram was made for a similar rock from the intermediate zone, in which all the olivine was completely serpentinized. This rock was slightly sheared and every pyroxene grain showed polysynthetic twinning. Figure 10 shows the plot of the twin planes of forty-one large diopsidic augite crystals. The poles to these twin planes show a polar concentration with a partial girdle.

The optical orientations of sixty olivine grains lying within three large pyroxene grains were plotted from a specimen collected within the central zone of the peridotite sill. This rock contains fresh olivine, pyroxene, hornblende, magnetite, and chlorite, and is moderately serpentinized. The olivine crystals are oriented as shown in Figure 11. Figure 12 shows a plot of the cleavage planes of the three large pyroxene grains in the same thin section and an idealized sketch of an olivine crystal in the preferred orientation of the olivine. These measurements revealed that randomly oriented pyroxenes contain well oriented olivine inclusions.

Interpretation of Petrofabric Data

The peridotite specimens exhibit a dimensional orientation of olivine grains. α, which equals the pole to (010), shows a distinct concentration at right angles to the most prominent 'S' plane, which lies parallel to the walls of the sill. β and γ lying in this plane also show a concentration with β oriented parallel to the strike of the sill and perpendicular to the second most prominent 'S' plane. The direction of stretching within the layering thus is parallel to the strike of the sill.

The petrofabric study permits two conclusions:

1. The olivine was intruded as euhedral and subhedral grains in a fluid matrix, and the intruded mass was 'stretched' approximately parallel to its present strike.
2. The pyroxene crystallized after the emplacement of the olivine.

The minor form orientation of the olivine may have resulted from the movement of the crystals in a liquid. Such movement did not result in pure olivine (dunite) layers or segregations, but probably produced small increases in the constituents of the fluid matrix in zones of maximum penetrative movement (border zones).

Certain factors argue against the Labrador peridotites having been intruded as masses of olivine crystals lubricated by thin films of water, according to the mechanism postulated by Sosman (1938). Such a mechanism would result in considerable shearing of the olivine grains. To explain the intrusion of a mush of unfractured, euhedral olivines, showing not even undulatory extinction, requires that the pyroxene be above its temperature of crystallization during intrusion in order to contribute towards the fluidity of the mass. The post-intrusion crystallization of pyroxene suggested by such a mechanism and substantiated at least partly by the petrofabric evidence has significance with regard to the temperature of intrusion and process of serpentinization.

This type of investigation should prove applicable to many fresh and partly altered peridotites.

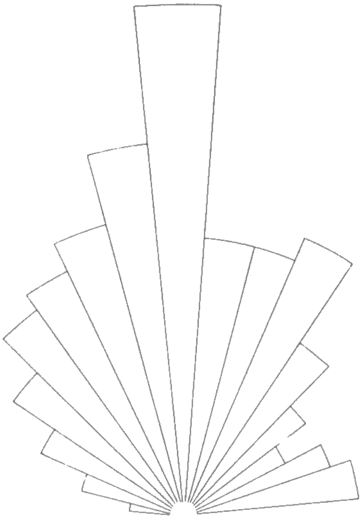

Figure 9. *Rosette diagram of long axes of 153 olivine grains in sixteen poikilitic pyroxene grains.*

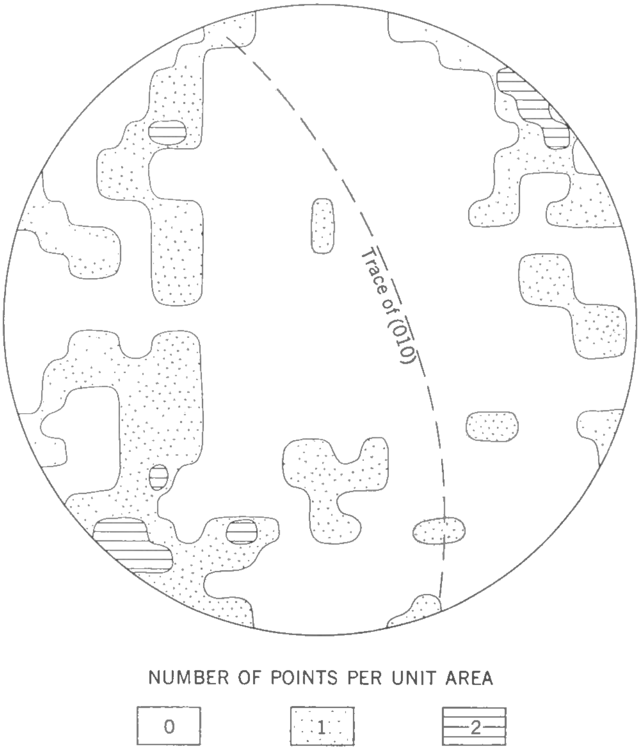

Figure 10. *Poles to twin planes (010) of forty-one pyroxene crystals from sheared peridotite.*

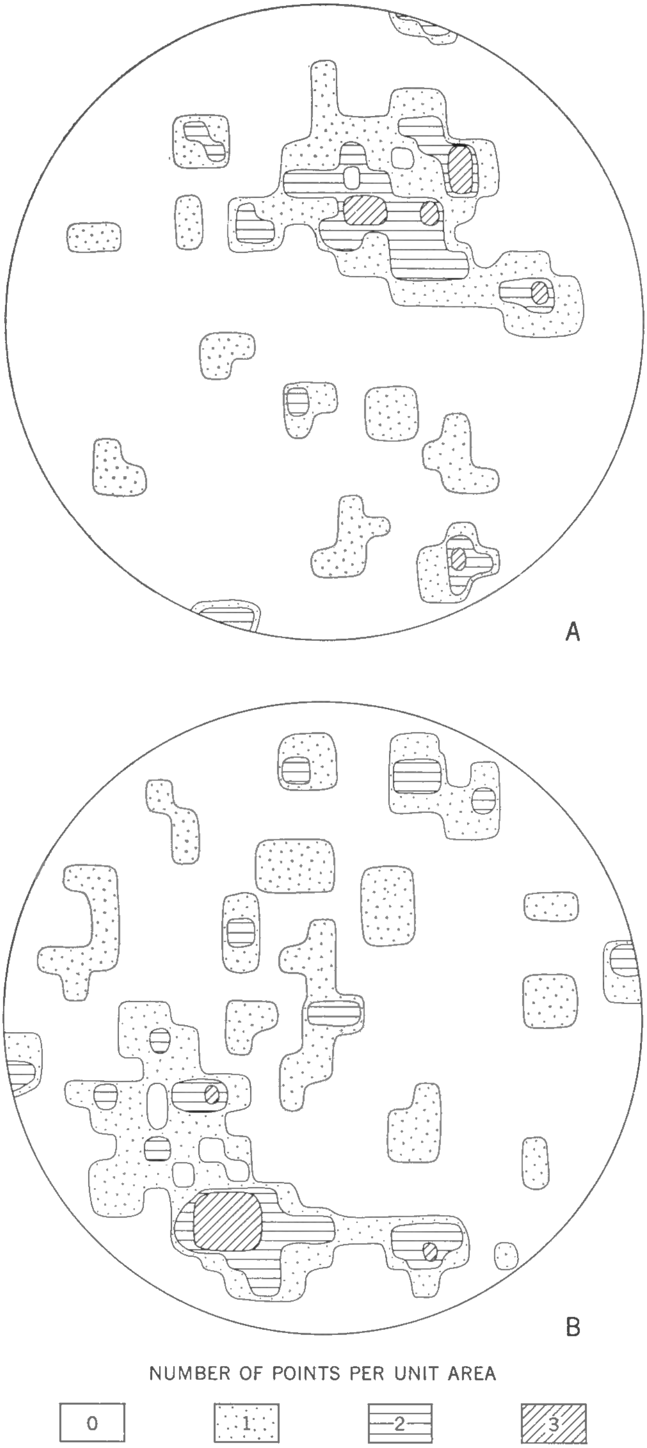

Figure 11. *Diagram of A, α axis; B, β axis of sixty olivine grains in three pyroxene grains.*

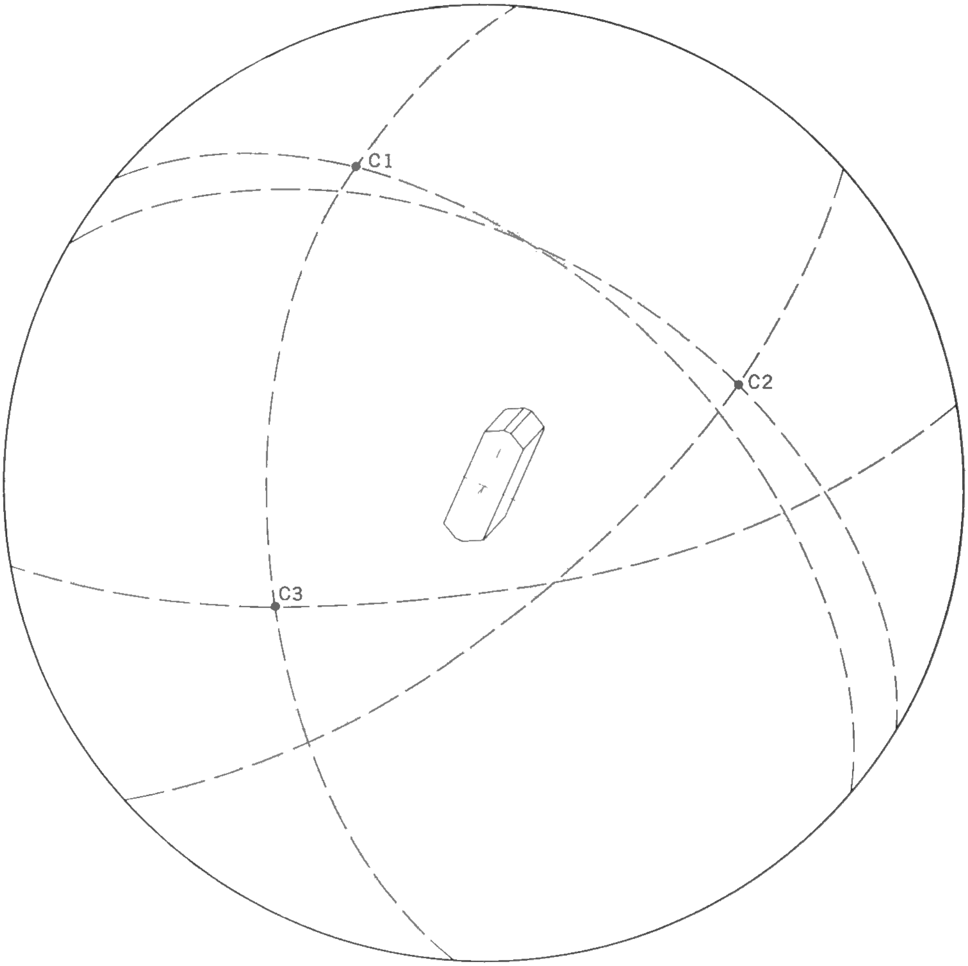

Figure 12. *Stereographic projection of cleavage (110) planes of the three pyroxene grains referred to in Figure 11. C1, C2, C3 are the intersections of the pyroxene cleavages. Idealized sketch of the olivine grains showing their orientation at the centre of the stereogram.*

RELATION OF THE ULTRABASIC ROCKS TO OVERLYING GABBRO

The following field and laboratory evidence provide a fairly clear indication of the relationship of the gabbro and ultrabasic rocks.

1. The gabbro overlies most of the ultrabasic sills in the central Labrador Trough area. Figure 3 shows an anticline of ultrabasic rock whose east limb is overlain by gabbro and whose west limb has either no gabbro or a very thin layer. Gabbro should overlie all the sills if it and the ultrabasic rock are the result of a differentiation in place.
2. The Cr content of the gabbro just above the top of the ultrabasic sill is much lower (by a factor of 10) than that of the ultrabasic rock nearby. Minor elements such as Cr, which are low in the olivine phase and high in the surrounding matrix (for example the pyroxene), would be high in the gabbro if the gabbro and ultrabasic rock were related.
3. The principal oxides SiO_2, Al_2O_3, MgO, and total iron as FeO in the gabbro show no marked variation in percentage across its width, but differ appreciably from their percentages in the ultrabasic sill (Fig. 13). A consistent change of at least some of these oxides would be expected if the two rocks resulted from differentiation in place.
4. The percentages of NaO, CaO, and to a lesser extent TiO_2, are quite different in the gabbro and ultrabasic rocks (Fig. 13). The NaO, for example, changes sharply from about 2 per cent in the gabbro to 0.15 per cent in the ultrabasic rock. The content of these elements in the ultrabasic sill should be proportional to the percentage of matrix around the olivine grains (40%). Furthermore field evidence does not permit the assumption that the gabbro was selectively albitized (by Na metasomatism) following differentiation.
5. The chemical composition of the gabbro is similar to that of the nearby meta-basalts and to other sills of gabbro in the region, which are spacially unrelated to ultrabasic rocks. The metamorphic grade and mineralogy of the gabbro are also similar to those of the nearby meta-basalts (epidote-amphibolite facies).

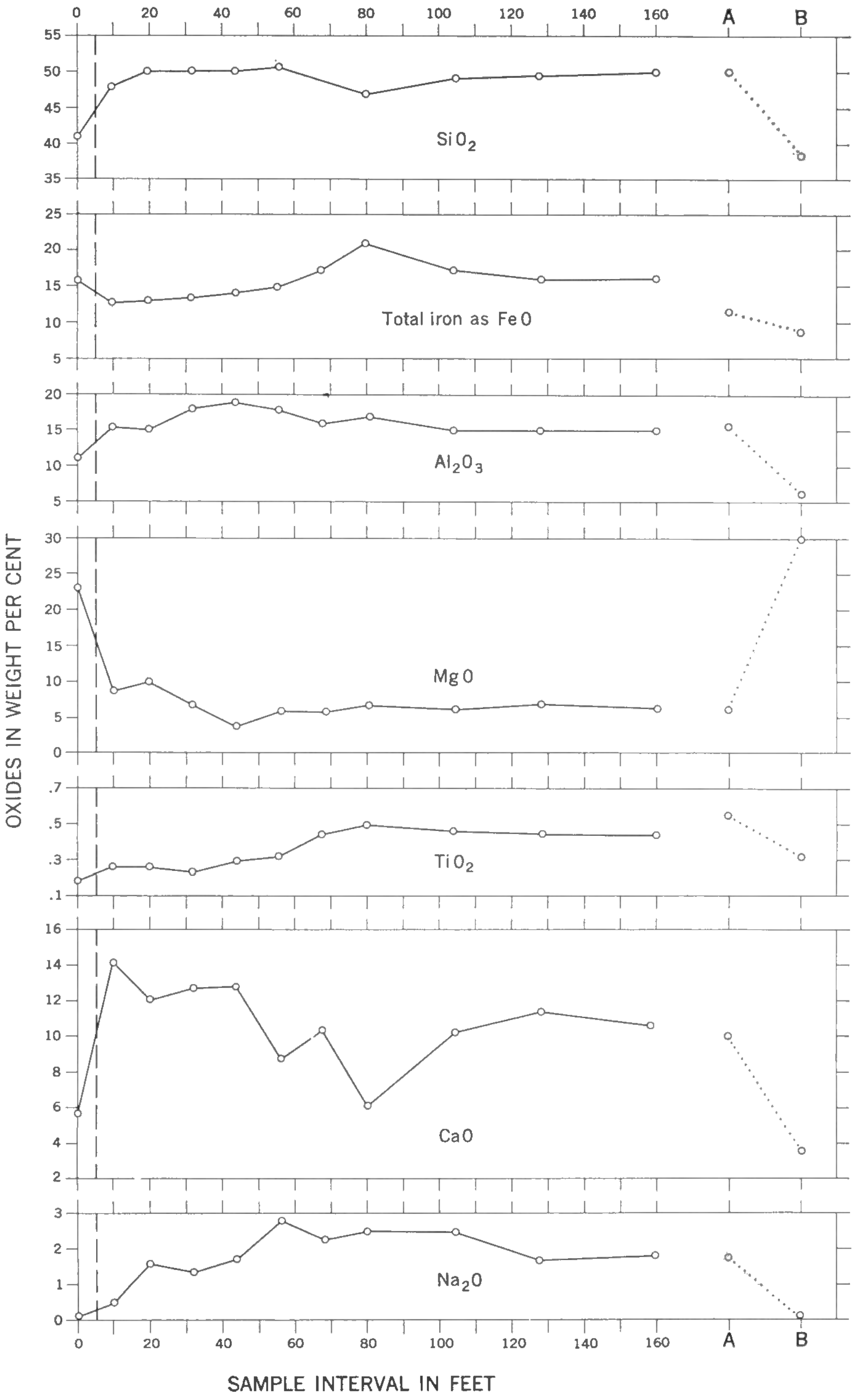

Figure 13. *Chemical variations from the top of Griffis Lake ultrabasic sill (left of dashed line) through an overlying meta-gabbro layer (right of dashed line). A is oxide per cent from analysis of meta-basalt in Table I; B is oxide per cent from analysis of Griffis Lake sill, Table III. (Analyses of ultra-basic sill and overlying meta-gabbro by H.B. Wiik, Helsinki, Finland.)*

SUMMARY AND CONCLUSIONS

1. Peridotite sills form a zone about 60 miles long on the eastern side of the Labrador Trough. Individual sills are more than 2,000 feet thick and have been traced along strike for more than 20 miles. The ultrabasic rocks were probably originally feldspathic peridotites with 50 to 60 per cent olivine. Faults related to regional deformation intersect the sills and suggest intrusion prior to or during folding. The sills are pervasively serpentinized and although they have features that are not typical of the Alpine type of ultrabasic intrusion their tectonic setting appears to be typical of such ultrabasic rocks.
2. Lavas, which form the most common country rock of the ultrabasic intrusions, are closely similar to tholeiite, quartz-diabase association. They have a low soda content.
3. The ultrabasic sills have a megascopic zoning, which is symmetrical about a plane parallel to the walls of the sill and passes through a central less serpentinized core. The outermost zones are characterized by much actinolite, the intermediate zones by the intensity of serpentinization, and the central zone (where present) by a relative lack of either of these types of alteration. This large-scale zoning reflects the movement of material, at right angles to the surface of the walls. The presence of a central less serpentinized zone suggests transport of water inward from the walls. There is no evidence of primary rhythmic mineralogical layering in the sills.
4. Silica and carbon dioxide metasomatism have resulted in alteration zones in two localities, one along a fault, the other along the crest of the Griffis Lake anticline. The metasomatism produced first a carbonate-talc-chlorite rock and later a carbonate-quartz-chlorite rock. This metasomatism occurred later than the initial serpentinization. Within the alteration zones there are carbonate-quartz veins. Cr, Al, and Fe were expelled from the space occupied by the veins and contributed to the formation of a sheath of pure chlorite along the borders of the vein.
5. The Griffis Lake sill was probably 50 to 60 per cent olivine; unserpentinized olivine remnants have a fayalite content of about 15 per cent. No significant variation in olivine composition was detected within the sill. The olivine crystals are discrete grains three quarters of a mm long and the unserpentinized olivine remnants show no evidence of strain. Only one generation of olivine appears to be present.
6. Diopsidic augite, whose original abundance is estimated at 20 to 30 per cent, forms anhedral, interlocking poikilitic crystals enclosing either olivine crystals or, more commonly, serpentine pseudomorphs of olivine. Pyroxene was more resistant than olivine to serpentinization and appears to have crystallized in place.
7. Serpentinization was volume-for-volume and exhibits two stages. The first serpentine has the optical characteristics of chrysotile, the second those of xylotile. In the outer zones xylotile is not present, but aluminous chlorite is abundant.

8. Members of the tremolite-actinolite-ferrotremolite series are present throughout the sills. There are two extremes, an early pleochroic brown ferrotremolite and a later colourless tremolite. The pronounced change in optical character suggests a break in conditions of formation. The ferrotremolite may be late magmatic, and the tremolite a later response to regional metamorphism.
9. Bulk chemical analysis indicates a higher calcium and aluminum content and a higher nickel to chromium ratio than is typical of rocks of the primary ultramafic magma series.
10. The amount and distribution of minor and major elements in the Griffis Lake sill are explained by its having been intruded as a mush of olivine crystals in a gabbroic silicate liquid. Such a mechanism could increase the liquid fraction towards the base and top of the sill and produce the chemical zoning.
11. The peridotite exhibits a dimensional orientation of olivine grains, which suggests intrusion of the olivine as euhedral and subhedral grain in a fluid matrix. Pyroxene appears to have crystallized after the olivine was oriented.
12. The ultrabasic sills are typically overlain by meta-gabbro, but field and laboratory evidence suggest that the two rock types are not differentiates in place. The relationship is explained by the spreading out of ultrabasic material beneath earlier massive gabbro layers.

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