

A STUDY OF THE EFFECT OF URALITIZATION UPON THE CHEMICAL
COMPOSITION OF THE SUDBURY NORITE

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CHAPTER I

THE PROBLEM

Most thin sections of Sudbury norite show that the pyroxenes have been altered to a fibrous amphibole, i.e., uralitized; only 5 to 10 per cent of the sections show remnants of fresh pyroxene. The main problem was to determine whether the process causing the change in mineral composition has materially affected the chemical composition of the rock and, if so, to determine the nature and extent of the changes. The solution of the problem may lead to a fuller understanding of the mechanism of uralitization in basic rocks.

From a more restricted viewpoint, the solution of the problem has an important bearing upon the interpretation of chemical analyses of the Sudbury norite in the literature. This is one of the most extensively analyzed intrusives in North America, and the analyses have been used by a number of investigators to support some theories and discredit others. Despite the fact that these workers recognized the severity of the alteration, no attempt was made to obtain uniformly fresh or altered samples. By correlating the alteration and the composition, the worth of the previous analyses and consequently the validity of the theories

CHAPTER II

SAMPLES USED IN THE STUDY

About 250 samples of the norite were collected near the Creighton mine section, Lot 2, Concessions 1, 2, and 3, Creighton township. The samples were collected below the zone of weathering. Thin sections of all samples were made. All of the work described in the following chapter was carried out on these thin sections and samples.

CHAPTER III

REVIEW OF THE LITERATURE

Considerable research has been carried out on the Sudbury intrusive due to the large amount of associated nickel-copper ore. Many papers dealing with various features of the intrusive are present in the literature. Most of these, however, are concerned with features of the intrusive or orebodies which have no connection to the present problem and will not be discussed.

I. GENERAL PETROGRAPHY

Petrographic descriptions of the norite have been furnished by a number of investigators, notably Walker (1897), Barlow (1904), and Phemister (1925). As these differ only on minor points from that given in the following chapter, no discussion is necessary.

II. ANALYSES OF THE NORITE AND THEIR USE

The first important work of this nature was done by Walker (1897), who collected five samples across the intrusive in the neighborhood of the Blezard mine and analyzed them. He concluded that there is a regular increase in acidity towards the centre of the intrusive.

No other complete series of analyses was made until

Knight (1923) analyzed seventeen samples from the intrusive in MacLennan township. From these he concluded that there is no gradual increase in acidity; in fact, "the most basic part of the eruptive is not along the outside, but from 1,500 to 2,100 feet from the outside edge."

Phemister (1925) attacked the problem in a different manner by collecting samples from eleven traverses across the intrusive and making mineral analyses of them. He concluded that the norite of the south range is most basic from one-half to three-quarters of its total width of outcrop from the basal contact. Above this, it becomes more acid by the development of a mesostasis of quartz and alkali feldspar and beneath it by the presence of quartz, which is a late crystallization.

Coleman, Moore, and Walker (1929), dissatisfied with the above and other conclusions, took samples across four complete sections of the intrusive and had them analyzed. The Capreol and Levack sections are on the north range, the Cameron Mine and Creighton sections on the south. They concluded "that the eruptive sheet is a unit formed by the segregation of a magma into a more basic portion, norite, passing without a break upwards into a more acid phase, micropegmatite."

The importance of these different sets of analyses

with regard to the nature and differentiation of the norite-micropegmatite is obvious; indirectly, they also have a bearing on the theories of ore formation. If Knight and Phemister are right in claiming that the most basic norite is not at the bottom of the intrusive, then the idea that the ore is at the bottom because it differentiated with the most basic part of the intrusive is ridiculous, and a hydrothermal theory of origin is more attractive.

A point which all of the above investigators appear to have overlooked is the fact that the deuterite alteration, particularly the uralitization, may have considerably altered the composition. Suppose, for example, that an exposure of fresh norite and another exposure in which all the pyroxene and part of the feldspar have gone to amphibole are found twenty feet apart, then which exposure should be sampled or does it make any difference? If the samples are chosen at random, they will be in different stages of alteration, and may not give a true picture of the composition gradient. It may be necessary to obtain samples which are at least fairly uniformly altered.

Some of the strange results which may be due to this late alteration are found in the various analyses. For example, an analysis of a sample forty-seven yards northwest of the Creighton mine gives only 0.69 per cent magnesia

(Knight, 1917); this can hardly be typical norite. Another analysis of Knight's 1,083 yards northwest of Creighton shows 1.56 per cent magnesia, but two analyses reported by Coleman (1929) straddling this one show 5.51 and 6.62 per cent magnesia respectively. When results like this are possible, the necessity of careful sampling is obvious.

This argument applies with much greater force in the use of mineral analyses, for the change in mode can be very great without having much effect upon the chemical composition. Furthermore, the nature of the method introduces large errors; as Larsen (1935) puts it, "Certain it is that many rocks, particularly coarse-grained rocks, are not well mixed on the scale represented by a thin section." This certainly applies to the norite, due to the habit of the ferromagnesian minerals to cluster. Larsen (1935) found that Rosiwal analyses of thin sections from the same hand specimen varied by from 2 to 10 per cent for the major constituents.

Phemister's work can not be criticized in this regard because all of his results are shown by graphs, and there is no account of the number of samples or thin sections that he used. However, it seems fair to point out the warning of Larsen (1935) that "the danger of basing far-reaching conclusions on a few Rosiwal determinations of

specimens from widely scattered outcrops is evident."

III. THE GENERAL NATURE OF URALITIZATION

The term uralite was first applied by Rose (1842) to a mineral with the crystalline form of a pyroxene and the structure of an amphibole. Clarke (1924) pointed out that the change is complicated in many cases by the simultaneous formation of epidote or zoisite. A separation of magnetite may occur and calcite may be formed due to the removal of lime. Generally augite alters to hornblende or actinolite and diopside to tremolite.

Dana (1914) said that the change begins on the outer surface of the pyroxene transforming it into an aggregation of slender amphibole prisms, parallel in position to each other and the parent pyroxene. When complete, the entire crystal is changed into a bundle of fibers. The amphibole conforms to actinolite in composition and optical characteristics.

The most prominent changes in composition are those in lime and magnesia. A number of analyses in Dana (1914) illustrate this; these are reproduced in Table I. Unfortunately, the corresponding rock types are not given, nor is it definitely stated that nothing else in the rock took part

in the reaction, so any changes in the bulk composition of rocks due to uralitization are not known.

The causes of uralitization have not been frequently investigated. Schwartz (1939) stated that it is a frequent product of hydrothermal alteration, but that it may occur during metamorphism of various types. Duparc and Hornung (1904) said that uralitization was not a case of hydrothermal alteration; instead, after the pyroxene had crystallized in the magma, it was acted on by the residual magma and the transformation occurred into patches of amphibole. In a later paper, Duparc (1908) said that the phenomena of uralitization is confined chiefly to feldspathic rocks and attributes it to a slightly later local injection of feldspathic magma. He cites cases in the Asiatic Urals where uralitization is caused by the injection of leucocratic dikes into pyroxenites.

The common occurrence of uralitization as a deuteric alteration effect has been noted by Colony (1923). In the end stages of crystallization some of the quartz and the alkalis are concentrated in liquid form of low viscosity and great penetrating power. At this stage olivine and magnesia-rich pyroxenes are susceptible to the alteration resulting in serpentization or uralitization. The ural-

ite formed shows a powerful penetrating power by invading the feldspar in every direction. He also notes that these phenomena may alter the chemical and mineral composition of the rock.

CHAPTER IV

EXPERIMENTAL RESULTS

I. GENERAL PETROGRAPHY

Primary minerals. Unaltered Sudbury norite is composed essentially of plagioclase, hypersthene, diallage, and quartz or granophyre. The order of crystallization of these minerals is clearly shown by the textural relations. Hypersthene was generally the first mineral to crystallize, although in some places it is later than plagioclase, indicating that the two minerals crystallized in part contemporaneously. The irregular shape of diallage and its habit of enclosing euhedral crystals of hypersthene and feldspar show that the diallage is later (Fig. 1). Quartz, or a granophyric intergrowth of quartz and soda feldspar, or rarely microcline, was the last important mineral to crystallize, as shown by its habit of filling in between the larger minerals in characteristic triangular or irregular shapes, and corroding the adjacent feldspar (Fig. 2).

Plagioclase occurs as euhedral laths of a distinctive brown color. Indices of refraction and extinction angles on Carlsbad-albite twins show it to be labradorite in composition, slightly closer to andesine than to bytownite.



Fig. 1. (xl2) Diplage showing typical irregular shape and enclosing euhedral plagioclase.



Fig. 2. (xl2) Quartz and granophyre interstitial to feldspar and slightly corroding it. (x-nicols.)

The feldspar is commonly zoned, though not extensively; generally only two bands occur.

The brown color of the feldspar is due to minute inclusions of ilmenite, hematite, or magnetite. An analysis of plagioclase from the south range showed it to contain 0.23 per cent titanium oxide, and 1.10 per cent ferric iron. In places these inclusions can be seen in the plagioclase as minute black needles in small patches, forming a grid structure almost at right angles, i.e., probably oriented along the crystallographic directions of the feldspar.

Hypersthene occurs in euhedral stubby prisms which show the typical pyroxene cleavage in cross-section. Clusters of hypersthene are common (Fig. 3). The mineral is pleochroic, rose to green, and has low birefringence, the highest color being first order yellow. It is length-slow, and has parallel extinction. It is biaxial negative with a large axial angle. The indices of refraction are $n_g = 1.699$, and $n_p = 1.692$.¹

Diallage is gray-green, occurring in irregular shapes. Generally it is much larger than the hypersthene grains, and commonly it occurs as large simple twins.

¹ Winchell's symbols are used because these values are compared to his values in a later section.



Fig. 3. (xl4) Cluster of hypersthene grains in all stages of alteration.

Birefringence is moderate, varying from first order yellow to violet. The maximum extinction angle is 45° . It is length-fast, measured from the cleavage with the smaller extinction angle. It is biaxial positive with a fairly large axial angle. The indices of refraction are $n_g = 1.710$ and $n_p = 1.689$.

Other primary minerals are biotite, hornblende, magnetite, apatite, and yellow sulphides. Primary biotite has a distinctive massive appearance, is only slightly pleochroic, and is generally found associated with or rimming magnetite. Primary hornblende is of minor occurrence; it is distinguished from secondary amphibole by its blue-green color and non-fibrous nature.

The occurrence of magnetite and apatite present special problems. Collins (1934) said that titaniferous magnetite is intergrown with pyroxene, hornblende, and biotite and therefore crystallized early. Certain features, however, are not in accord with this idea. In the first place, magnetite shows the same filling-in shapes as the late quartz where it occurs in feldspar. Secondly, biotite, which is not an early crystallizing mineral, invariably forms a thin rim around the magnetite grains.

Apatite also occurs as euhedral crystals intergrown with the ferromagnesian minerals or around the edges of

them. It may be clustered around grains of magnetite, and in general those sections high in magnetite are also high in apatite. A few grains were found to be later than feldspar.

The highly variable amount of apatite and magnetite in different sections is puzzling. In some sections they account for almost 10 per cent of the rock, whereas in others there is virtually none. If they were the very earliest to crystallize, some sort of segregation at the bottom of the norite would be expected; if they crystallized at about the same time as the ferromagnesian, a uniform distribution throughout the norite would be expected. As neither is the case, there may be another explanation.

Alteration minerals. The nature of the uralitic alteration is more easily observed in hypersthene than in the diallage, which has a lamellar structure controlling the size and distribution of the fibrous material. In hypersthene the alteration always begins at the outer border and progressively works its way inwards by veining until only isolated remnants of the fresh pyroxene remain (Fig. 4); in diallage, because of the structural control, most of the mineral may be altered and yet have partly fresh borders.

Hypersthene may alter directly to uralite or may pass through a bastitic phase. The serpentine, which was



Fig. 4. (x14) Hypersthene almost completely altered to serpentine. Diallage still fresh.

identified by its X-ray powder pattern, is gray to light green in color, has a massive or aggregate structure, and has very low birefringence. The alteration is accompanied by a separation of small grains of magnetite in both hypersthene and diallage.

The uralite is a pale gray to green color, occurring in fibrous pseudomorphs after pyroxene (Fig. 5). Pleochroism is slight to medium, probably because of the loss of iron due to the separation of magnetite. Birefringence is low, the highest color being first order yellow. The maximum extinction is 15° and the mineral is length-slow. An interference figure could not be obtained. Indices of refraction are $n_g = 1.643$ and $n_p = 1.631$.

With more intense alteration, the uralite recrystallizes around the outer edges to a darker green, more pleochroic amphibole. A mixture of small biotite plates may accompany the uralite. With extreme alteration, this mixture or the uralite alone spreads out through the rock replacing the feldspar along grain boundaries, twinning planes, or in irregular patches (Fig. 6). In one or two sections the uralite has gone completely to biotite.

In most sections the alteration by the late quartz and granophyre is not important as it only fills in the spaces between grains and corrodes slightly the adjacent



Fig. 5. (x10) Fibrous pseudomorph of uralite after hypersthene. (x-nicols.)



Fig. 6. (xl8) Uralite replacing feldspar along grain boundaries and in irregular patches.

feldspar. In a few sections it does become prominent, replacing large portions of the feldspar. The pseudomorphs of uralite after pyroxene are in some sections a mixture of amphibole needles and small quartz granules. In a few sections they are a mixture of amphibole needles and carbonate grains.

Alteration of the plagioclase is by no means as common or intense as that of the pyroxenes, but even in the freshest norite an incipient type of alteration occurs at the centre of the large feldspar grains. Rarely this alteration becomes intense and the large feldspar crystal is packed with small crystals. The small crystals are colorless and have good crystal boundaries but no distinctive crystalline shape. They have very low birefringence and a higher index of refraction than the feldspar. The feldspar invariably loses its typical brown color at the point where these grains crystallize, suggesting that the excess iron or titanium causing the brown color is being used up in the formation of a silicate mineral. The only mineral which would fit this theoretical composition is zoisite. Zoisite, however, has slightly higher birefringence and usually occurs as aggregates rather than as single crystals.

With severe alteration, the feldspar may break down

completely, lose its brown color, and the rock becomes a mixture of clear albite, epidote, and amphibole.

Calcite and chlorite veinlets are present but are rare.

II. MECHANICAL ANALYSES

A series of four thin sections showing a complete gradation in the degree of uralitization of the pyroxenes were chosen for chemical analysis. The purpose of making analyses of such a series was to determine whether the change in mineral composition had altered the bulk chemical composition of the norite.

However, a brief examination of a number of thin sections showed an apparent erratic distribution of the ferromagnesian. The amount of quartz also appeared to change from section to section. If these apparent variations were real, the results of chemical analyses might be seriously affected. Before making chemical analyses, therefore, mineral analyses of the sections were made to determine whether the total ferromagnesian content and the quartz content remained constant from sample to sample.

Rosiwal analyses. Four sections showing a complete gradation from fresh to altered norite were selected and

analyzed, using an integrating stage. Wherever possible, blank spaces in the thin section were added in as the proper mineral. Minor constituents, e.g., magnetite, biotite, were neglected.

The results listed in Table II show wide variations in the mineral composition of the specimens. The total ferromagnesian content (hypersthene plus diallage plus urallite) is 26 per cent in the fresh norite but is only 18, 21, and 22 per cent respectively in the three altered sections. The quartz content ranges between 7 and 11 per cent in the four sections. This may mean that a large variation in mineral composition from specimen to specimen does exist. On the other hand, perhaps a single thin section will not give a reliable analysis of a given sample.

To test the latter idea thoroughly, seven thin sections were made from one and one-half inches of sample by cutting the sections at the closest possible intervals. All the sections were analyzed using the integrating stage.

The results in Table III show conclusively that an analysis of a single thin section is not adequate for a medium-grained rock. The amount of plagioclase in the seven sections varied from 55 to 73 per cent, hypersthene from 9 to 20 per cent, diallage from 4 to 13 per cent,

TABLE II

ROSIWAL ANALYSES OF A SERIES FROM FRESH TO ALTERED NORITE

Constituents	1	2	3	4
Plagioclase	65	73	72	67
Hypersthene	13	7	1	
Diallage	6	2	1	2
Quartz	9	9	7	11
Uralite	7	9	19	20

1. Slightly altered norite.
2. Norite showing medium grade of alteration.
3. Norite with only a few unaltered remnants of pyroxene.
4. Completely altered norite.

TABLE III
ROSIWAL ANALYSES OF CONSECUTIVE SECTIONS
FROM A SINGLE SAMPLE

Sample	Plag.	Hyp.	Diall.	Qtz.	Ural.
5-A	64	16	7	10	3
5-B	66	14	7	9	4
5-C	70	12	4	11	3
5-D	55	20	13	7	5
5-E	59	17	13	9	3
5-F	73	9	6	9	3
5-G	64	14	8	12	2
Average	65	14	8	10	3

5-A, 5-B, etc. Fresh norite.

quartz from 7 to 12 per cent, and urallite from 2 to 5 per cent. At least five analyses should be averaged to get reliable values for the mineral composition. The sections used were about 300 sq. mm. in area; therefore the total area measured should be approximately 1500 sq. mm. The average grain size of the Sudbury norite is about one sq. mm.

Planar analyses. Two independent planar analyses of sample no. 1 were made as a check on the accuracy of the linear analyses. The thin section was projected on to a sheet of blank paper and all of the major constituents except plagioclase were traced on to the paper, the remaining blank area representing plagioclase. The respective areas of the different minerals were measured with a planimeter.

A number of difficulties were encountered with the method. Quartz could not be easily distinguished from plagioclase on the screen; nor could the intimate mixture of hypersthene and urallite be accurately separated. Furthermore, the quartz grains were too small to be measured accurately with the planimeter.

These difficulties are apparent in the results given

in Table IV. The amounts of hypersthene, diallage and urallite found by planar analysis agree within 1 or 2 per cent for those found by Rosiwal analysis. However, the amount of plagioclase found by planar analysis is 9 per cent more than that found by Rosiwal analysis, and the amount of quartz is 5 per cent less, indicating that much of the quartz has been estimated as plagioclase in the planar analyses. If these two constituents are added together, the results give a fair agreement with the Rosiwal analysis.

Grain counting. Analysis by grain counting was tried in order to avoid the laborious procedure of making four or five thin sections from each sample for one analysis. About thirty grams of each sample were pulverized in a diamond mortar. Each sample was then sieved, collecting the minus 60-plus 100, minus 100-plus 200, and minus 200 mesh fractions. The procedure of crushing and sieving was standardized as much as possible, with the result that about the same weight of fraction of each sample was obtained.

Grain counts were made on the minus 100-plus 200 mesh fraction. The grains were immersed in index oil ($n = 1.55$) on a glass slide and the slide was run across the field of the microscope in a straight line using the integrating stage. Only those grains intercepting the

TABLE IV
COMPARISON OF ROSIWAL AND PLANAR ANALYSES

Constituents	1	1-A	1-B
Plagioclase	65	75	73
Hypersthene	13	10	12
Diallage	6	5	5
Quartz	9	5	4
Uralite	7	5	6

1. Rosiwal analysis of slightly altered norite.
 1-A. Planar analysis by T. A. Oliver of same thin section.
 1-B. " " " H.D.B. Wilson " " " "

cross-hairs were counted. Counts were made on three separate slides for each sample; about 350 grains were counted on each slide, making a total of 1000 grains.

This method could not be used for determining quartz as most of the quartz grains were not freed by the crushing but remained attached to feldspar grains. The percentage of quartz varies relatively little from section to section, as shown in Table III, so it was determined by making Rosiwal analyses of two thin sections for each sample. The hypersthene and urallite had to be grouped together as they were not completely separated by the grinding.

The results of the grain counts are shown in Table V. Sample no. 5 is the same one on which the seven consecutive Rosiwal analyses were done. The results from the grain counts for this sample agree within 1 per cent of the average of the seven Rosiwal analyses. The close agreement indicates the accuracy of the method of grain counting.

The results also show that the total amount of ferromagnesian is almost constant in specimens of fresh and altered norite. The total content of ferromagnesian varies between 26 and 28 per cent. These results eliminate the possibility of an erratic distribution of ferromagnesian in different specimens seriously affecting the results of

TABLE V
ANALYSES OF AN ALTERATION SERIES BY GRAIN COUNTING

Constituents	5	6	7	8
Plagioclase	64	64	64	61
Hypersthene plus uralite	18	21	23	28
Diallage	8	5	5	
Quartz	10	10	8	11

5. Fresh norite.
 6. Slightly altered norite.
 7. " " "
 8. Completely altered norite.

chemical analyses.

III. CHEMICAL ANALYSES

Analyses of rock samples. Samples no. 6 and 8 were chosen for chemical analysis. No. 6 is norite in which the pyroxenes are unaltered or only slightly altered whereas no. 8 is norite in which all of the pyroxene has been altered to fibrous amphibole. The purpose of analyzing these two specimens was to determine whether the change in mineral composition from pyroxene to amphibole had also changed the chemical composition of the rock in any important respects.

The results in Table VI show little chemical difference between fresh and altered norite; the differences are so small that they may be within the range of experimental error. Silica and alumina appear to be added in the altered sample, whereas there is an apparent decrease of all the other constituents except the alkalies and water. These differences are slight, however, and may not be significant. The water content of both samples is surprisingly low, but a redetermination gave similar results.

Separation of pure minerals. The differences in composition of the fresh and altered rock are small, but possibly some of the differences are real. To determine

TABLE VI
CHEMICAL ANALYSES OF FRESH AND ALTERED NORITE

Constituents	6	8
SiO ₂	53.30	54.42
Al ₂ O ₃	17.60	19.65
Fe ₂ O ₃	2.88	1.87
FeO	7.13	6.07
CaO	9.05	8.74
MgO	6.06	5.15
Na ₂ O	2.58	2.80
K ₂ O	1.34	1.53
H ₂ O	0.22	0.30
Total	100.16	100.53
S. G.	2.87	2.88

6. Fresh norite.
8. Altered norite.

whether or not this is so, pure hypersthene, diallage, and uralite were separated from crushed rock and analyzed.

Two samples about fifteen feet apart, one fresh and the other altered, were chosen for the separation. Pure uralite was obtained with ease from altered norite by separating the minus 35-plus 60 mesh fraction in Clerici's solution. The first concentrate of uralite was purified by two further separations. Large magnetite grains were extracted with a magnet.

A test for purity was made by immersing part of the concentrate in index oil and counting pure, mixed, and foreign grains. Mixed grains were mostly uralite plus feldspar; foreign grains were mostly opaques and a few apatites. The test showed that the uralite was 97 per cent pure.

The separation of hypersthene and diallage was complicated by the fact that the specific gravity of diallage is intermediate to that of hypersthene and uralite. Therefore, hypersthene partially altered to uralite has about the same gravity as the diallage, and these come down together in the separation. By repeated separations in Clerici's solution about 1.5 grams of pure hypersthene was removed from the mixture of altered hypersthene and diallage. This concentrate was found to be 98 per cent pure,

Analyses of the minerals. The altered minerals are

the foreign and mixed grains being the same kind as in the uralite.

Pure diallage could not be obtained by this method for the reason stated above. Coleman (1929) found that the monoclinic pyroxene (which they called augite) could be separated from the hypersthene with a Hallimond separator. However, the magnetic separator available was not sensitive enough to distinguish between the two pyroxenes. Due to the failure of these methods, the diallage was finally picked by hand under the binoculars.

In this method, fresh norite was crushed, sieved, and a concentrate of heavy minerals obtained by separation in Clerici's solution. Diallage was picked from the minus 35-plus 60 and the minus 60-plus 100 mesh fractions under the binoculars with a two-haired brush which was then dipped into a small beaker of water, freeing the mineral. It is readily distinguished by its dark green color and flat, tabular appearance whereas hypersthene is pink and has a stubby prismatic appearance. About half a gram was picked in this manner. The concentrate was further purified by separation in Clerici's solution. The amount used for the analysis was estimated to be 95 per cent pure.

Analyses of the minerals. The mineral analyses are

shown in Table VII, along with the calculated formulae of the minerals.

Only the main portion of hypersthene and diallage was completed, owing to the small amount of these minerals available. Diallage contains approximately 3 per cent more alumina, 15 per cent more lime, 8 per cent less ferrous iron, and 7 per cent less magnesia than hypersthene.

The analysis of uralite showed it to be roughly intermediate in composition to hypersthene and diallage. The first analysis of uralite showed a deficit of 4 per cent. This was considered to be an analytical error but a second analysis gave similar results.

The nature of this analytical deficit in amphiboles has been discussed by Jakob (1935, 1937), who found that it is generally absent from asbestiform (one-dimensional) varieties but never from compact (three-dimensional) varieties. The deficit was once thought to be due to an excess of molecular oxygen but Jakob has shown that it is actually caused by water given off above 1000° C. This water is more or less reduced to hydrogen by bivalent titanium. His views are confirmed by Heng Sheng Wang (1939) who tabled Niggli values of ninety-four hornblendes and found that the varying deficit is due to the difficulty in driving off water.

TABLE VII
CHEMICAL ANALYSES OF HYPERSTHENE, DIALLAGE, AND URALITE

Constituents	1	2	3	4	5	6
SiO ₂	52.11	51.61	51.48	53.21	52.34	54.3
Al ₂ O ₃	1.22	4.17	5.78	4.24	5.01	
Fe ₂ O ₃	1.65		2.26	(2.26)	2.26	18.4
FeO	19.96	11.48	13.04	(13.04)	13.04	
CaO	1.63	16.09	7.39	6.58	6.98	8.4
MgO	22.16	15.49	14.46	15.65	15.06	18.1
Na ₂ O			0.80		0.80	0.8
K ₂ O						
H ₂ O			0.72	0.70	0.71	
Totals	98.73	98.84	95.93	96.48	96.20	100.0
S. G.	3.47		3.07			

1. Analysis of hypersthene, Mg₂FeSi₃O₉.
2. " " diallage, Ca₂(Mg,Fe)₄Si₆O₁₈.
3. " " uralite, Ca(Mg,Fe)₅Si₈O₂₂(OH)?.
4. Check analysis of uralite.
5. Average analysis of uralite.
6. Average of uralite recalculated to 100 per cent by taking addition of silica plus alumina and water (including the deficit) into account.

Another possibility pointed out by Larsen (1938) is that the errors in analyzing amphiboles may be due to the presence of fluorine in the amphibole.

Calculations based on the analyses. The original problem was to determine whether the uralitization was accompanied by any change in chemical composition. This is now possible by making simple calculations involving the constituents of hypersthene and diallage, and the ratio of hypersthene to diallage in the rock. The composition of uralite theoretically calculated from the composition of hypersthene and diallage should agree with the composition of uralite found by chemical analysis if no changes in chemical composition accompany the uralitization. Some assumptions and adjustments have to be made before making the calculations.

If the assumption is made that none of the constituents except silica plus alumina and water change then the other constituents must be adjusted to 100 per cent before a true comparison can be made. The assumption that there is an actual gain in silica plus alumina agrees with the results of the rock analyses, in which there was a total gain of about 3 per cent in these constituents in the

altered rock. In the uralite there is a gain of 3.1 per cent in silica plus alumina and 4.6 per cent in water (including the deficit), or a total of 7.7 per cent. This amount is split proportionally among total iron, lime and magnesia as shown in Table VII. The amount of total iron, lime, and magnesia in the uralite should be equivalent to that in the two pyroxenes when the ratio of these two minerals in the norite is taken into account, if the above assumptions are valid.

The ratio of hypersthene to diallage was determined by making Rosiwal analyses of three different thin sections of the analyzed norite. The average ratio of hypersthene to diallage was equal to 1.6 to 1. Grain counts gave a ratio of 1.5 to 1. Ten other sections of fresh norite gave an average value of 1.8 to 1. Compensation should be made for the specific gravities of the two minerals since the ratio found by these methods is a volume, not a weight ratio. The difference, however, is within the limit of error. The value finally used was 1.7 to 1 which means that 0.63 parts hypersthene plus 0.37 parts diallage form 1.0 part uralite.

Using this ratio, a simple calculation shows that theoretically, uralite derived from hypersthene and diallage should contain 18.0 per cent total iron whereas analyzed

uralite adjusted to 100 per cent contains 18.4 per cent ferrous iron. Theoretically, the uralite derived solely from the hypersthene and diallage should contain 6.9 per cent lime and 19.6 per cent magnesia; it actually contains 8.4 per cent lime and 18.1 per cent magnesia.

If the above calculations are absolutely correct, it means that in the uralite formed from the pyroxenes by alteration 0.4 per cent total iron and 1.5 per cent lime have been added, and 1.5 per cent magnesia has been lost. However, when the numerous sources of error, e.g., the separation of pure minerals, the chemical analyses themselves, the determination of the hypersthene to diallage ratio, are considered, the differences are probably within the limits of error.

The conclusion is that the only changes in chemical composition in the uralitization of the Sudbury norite are a slight addition of silica plus alumina (which may not be significant), and water. Furthermore, as the pyroxenes only account for about one-third of the norite by weight, any real changes in composition will give much smaller absolute differences in the rock analyses.



IV. OTHER PROPERTIES OF THE ANALYZED MINERALS

Optical properties. Considerable work has been done on the relationship between composition and optical properties of the pyroxenes and amphiboles. Winchell (1933) has published graphs showing the relationship between the indices of refraction of these minerals and their composition and other properties. The values obtained from his graphs and the values observed in hypersthene, diallage, and uralite are compared in Table VIII. The values agree fairly well.

The results of X-ray work. Powder pictures of the analyzed minerals were taken. The readings are recorded in Table IX. For comparative purposes the A.S.T.M. card index readings for hypersthene, diopside, and actinolite are also reported. The minerals agree well with those in the index.

Nature of the uralite. The secondary amphibole of the norite may have a constant composition or two distinct amphiboles may have been formed from the two pyroxenes. If there are two, then the hypersthene and diallage merely underwent hydration in the deuteric alteration, but if there is only one of constant composition then there must have

TABLE VIII
COMPARISON OF PROPERTIES OF THE ANALYZED MINERALS
WITH THOSE FROM WINCHELL'S GRAPHS

Properties	1	2	3	4	5	6
Amount MgO	22	28	15	14		
" FeO	20	15	11	8		
" CaO			16	24		
2V	Large	78°	Large	60°	?	85°
Birefring.	Low	.0012	Med.	.025	Low-med.	.025
Z c			45°	41°	15°	15°
S. G.	3.47	3.40			3.07	3.10

1. Hypersthene from Sudbury norite.
2. Hypersthene from Winchell's graph for enstatite-hypersthene system for $n_g = 1.699$.
3. Diallage from Sudbury norite.
4. Diallage from Winchell's graph for the diopside-hedenbergite system for $n_g = 1.710$.
5. Uralite from Sudbury norite.
6. Actinolite from Winchell's graph for the tremolite-ferrotremolite system for $n_g = 1.643$.

TABLE IX
X-RAY INVESTIGATION OF THE ANALYZED MINERALS

1		2		3		4		5		6	
I	d	I	d	I	d	I	d	I	d	I	d
1	3.34	3.	3.36			1	4.50	4	4.56	1	4.58
10	3.20	10	3.20			1	4.16	2.	4.18	2	4.30
2	2.99	2	2.98			2	3.41	1	3.86	3	3.92
5	2.88	8	2.890	1	3.20	5	3.26	4	3.37	6	3.42
2	2.72	3	2.725	10	2.99	10	3.00	3	3.27	6	3.28
7	2.56	5	2.550	1	2.89	3	2.911	6	3.13	9	3.14
3	2.49	5	2.482	1	2.72	2	2.570	1	2.95	6	2.94
1	2.26	1	2.233	9	2.53	10	2.523			5	2.79
3	2.12	5	2.112			1	2.441	9	2.64	10	2.70
1	2.03	2	2.026	1	2.30	2	2.303	3	2.61	6	2.59
1	2.00			1	2.22	2	2.209	1	2.54	8	2.54
1	1.96	4	1.957	1	2.13	5	2.128	2	2.33	7	2.32
1	1.79	4	1.784	1	2.03	3	2.038	1	2.28	3	2.28
1	1.74					3	2.010	2.	2.17	8	2.15
1	1.62					4	1.828	1	2.03	4	2.03
1	1.59	6	1.599	1	1.76	7	1.744			7	2.01
2	1.52	5	1.527			2	1.661			2	1.930
5	1.48	8	1.486	6	1.63	10	1.616	1	1.87	3	1.881
1	1.43					4	1.497			4	1.863
4	1.39	6	1.389	4	1.42	9	1.418	1	1.81	5	1.806
		etc.				etc.				5	1.679
								3	1.65	8	1.642
								3	1.63	3	1.614
								1	1.59	8	1.576
								1	1.55	3	1.551
										5	1.527
								2	1.51	9	1.507
								3	1.44	10	1.432
										etc.	

1. Hypersthene, chemically analyzed.
2. Hypersthene, A.S.T.M., II, 1133.
3. Diallage, chemically analyzed.
4. Diopside, A.S.T.M., II, 1383.
5. Uralite, chemically analyzed.
6. Actinolite, A.S.T.M., II, 1908.

been an interchange of calcium, magnesium, and iron ions.

The optical properties do not afford much evidence. The uralite formed from hypersthene does appear different from that formed from diallage in slightly altered sections. The uralite derived from diallage has slightly higher interference colors and is finer-grained than that from hypersthene. The lamellar structure of diallage may control the size of the alteration product, however. Another feature in favor of the two-amphibole idea is that the hypersthene seems to be much more easily altered than the diallage; some sections show much of the hypersthene severely altered whereas much of the diallage is still fresh. This might be an illusion due to the greater amount of hypersthene in a section. In severely altered norite, all of the uralite has the same appearance, suggesting a constant composition.

As mentioned before, hypersthene occurs in euhedral prisms whereas diallage has a most irregular habit. In the early stages of alteration, the secondary amphibole retains these distinctive shapes. It was therefore possible to polish a section of rock and scrape out with a diamond point enough of the two types to make powder pictures of them.

The results in Table X are again inconclusive. The two types certainly have the same structure as actinolite

TABLE X

X-RAY COMPARISON OF URALITE FROM BOTH PYROXENES

1		2		3	
I	d	I	d	I	d
8	5.08				
1	4.56			1	4.58
1	4.26	2	4.38	2	4.30
				3	3.92
10	3.37	1	3.34	6	3.42
1	3.25			6	3.28
3	3.13	10	3.15	9	3.14
1	2.93	1	2.95	6	2.94
		1	2.82	5	2.79
3	2.72	10	2.72	10	2.70
1	2.63	1	2.60	6	2.59
1	2.53	1	2.54	8	2.54
1	2.46				
1	2.37	1	2.33	7	2.32
1	2.28	2	2.28	3	2.28
1	2.18	1	2.16	8	2.15
1	2.02	1	2.02	4	2.03
				7	2.01
				2	1.930
		1	1.88	3	1.881
				4	1.863
1	1.82	1	1.81	5	1.806
				5	1.679
1	1.66	1	1.65	8	1.642
		1	1.62	3	1.614
		1	1.59	8	1.576
1	1.54	1	1.54	3	1.551
1	1.51	1	1.51	5	1.527
				9	1.507

1. Uralite derived from hypersthene.
2. Uralite derived from diallage.
3. Actinolite, A.S.T.M., II, 1908.

but the method may not be sensitive enough to determine slight differences in composition.

An attempt was made to obtain indices of refraction on the two types but this was unsuccessful due to the extreme fineness of the material scraped out by the diamond point.

The above work indicates that there may be differences in the composition of uralite derived from hypersthene and that derived from diallage; the nature and extent of any differences, however, could not be determined.

CHAPTER V

CONCLUSIONS

The conclusions based on the above work appear below.

(1) The results of chemical analyses of fresh and altered norite showed that no important changes in the chemical composition of the rock occur due to the process causing uralitization. This fact was confirmed by analyzing hypersthene, diallage, and uralite; the results showed that water and possibly a small amount of silica and alumina are added in the formation of uralite whereas the differences in the other constituents were within the limits of experimental error.

However, no samples of norite were analyzed in which the feldspar had been largely replaced by the uralite or late quartz. Material of this kind might be radically altered in composition.

(2) The results of the mechanical analyses showed that the distribution of the ferromagnesian minerals and the interstitial quartz is fairly constant in fresh and altered norite, i.e., the percentage of hypersthene plus diallage in the fresh rock equals the percentage of uralite in nearby altered rock.

(3) A Rosiwal analysis of one thin section will not give reliable values for the mineral composition of the rock. Analyses of two thin sections from the same sample showed that the amount of plagioclase differs by as much as 18 per cent, and the other constituents by from 3 to 10 per cent. Four of five thin sections should be analyzed to obtain reliable values.

(4) Other investigators using chemical and mineral analyses of the norite have neglected the possible effect of the alteration upon their results. This work shows that the alteration would not make much difference as long as only the pyroxenes in the samples were altered. Samples in which the feldspar had been altered might not give results which could be reliably compared to those from other samples.

(5) The process of uralitization in the Sudbury norite appears to be carried out by a residual liquid of aqueous character, carrying small amounts of silica, alumina, and possibly fluorine. In the first stages of the alteration simple hydration of the pyroxene takes place, resulting in serpentization or uralitization of the hypersthene and leaving the diallage relatively unaltered. With increasing alteration an interchange of calcium, magnesium, and iron ions between the two pyroxenes may occur, resulting

in the formation of an amphibole of constant composition. These points, however, are not definite.

(6) The problem of the distribution of serpentization and uralitization in the intrusive was not solved. The writer suspects that the serpentization of hypersthene is largely confined to the bottom of the intrusive where there is not as much diallage in the rock; an extremely careful job of sampling the intrusive would be required to determine this point.

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APPENDIX

SAMPLE NUMBERS USED IN THESIS WITH CORRESPONDING CORE NUMBERS

Sample numbers	Core numbers
1	3-260
2	3-270
3	3-280
4	3-290
5	1-1056
6	1-1060
7	1-1080
8	1-1070