UNIVERSITY OF MINNESOTA

MINNESOTA GEOLOGICAL SURVEY

WILLIAM H. EMMONS, DIRECTOR

BULLETIN 28

THE GEOLOGY OF THE ANORTHOSITES OF THE MINNESOTA COAST OF LAKE SUPERIOR

BY

FRANK F. GROUT

AND

GEORGE M. SCHWARTZ

MINNEAPOLIS · 1939

THE UNIVERSITY OF MINNESOTA PRESS

PRINTED IN THE UNITED STATES OF AMERICA

FOREWORD

Anorthosites on the north shore of Lake Superior have long been known, and have been the subjects of some discussion, but their possible uses have not been carefully studied. Although two unsuccessful attempts have been made to use them for abrasives, their possibilities as ceramic and building materials have not been thoroughly tested. In recent years possibilities for such use of these materials have increased.

The first problem of the present study has been to determine the actual size and distribution of the north-shore anorthosite occurrences; also to present observations on the evidences of their origin, and to describe the geology of the district in sufficient detail so that remapping would not be necessary. The second problem has been to test the most promising masses as to their availability for commercial purposes.

Field work was begun in 1931 and was continued as opportunity offered through 1937. There are no topographic maps of the area except along some of the streams, but the town plats of the United States Land Office served as base maps. The recent aerial photographs, made for the Forest Service and obtained from the Standard Air Service, proved very helpful in the area around Cramer. Thanks are also due the Minnesota Highway Department for maps of Highway No. 61; and to the county engineer's office of Lake County at Two Harbors for various materials, of which a right-of-way map of the abandoned railroad proved particularly helpful. The Minnesota Division of Forestry cooperated in the work; particular thanks are due O. M. Ekbeck, patrolman. Surveys of roads constructed by the Finland camp of the Civilian Conservation Corps, as well as a special survey of the east branch of the Baptism River, were furnished by officials of the camp. Efficient service was given in the field by Stanley Sundeen, O. H. Kristofferson, L. C. Lancaster, Lincoln Page, Roger Swanson, F. C. Kruger, F. B. Hanley, and Benjamín Alvarado. The drafting was done largely by Don Nichols, R. I. Kellum, Harold Maiers, and Benjamín Alvarado. Most analyses of anorthosite and other rocks were made by R. B. Ellestad of the University of Minnesota Rock Analysis Laboratory.

F. F. G.
G. M. S.

CONTENTS

LIST OF FIGURES

LIST OF PLATES

The Geology of the Anorthosites of the Minnesota Coast of Lake Superior

INTRODUCTION

The northeast corner of Minnesota, lying north of Lake Superior and comprising Cook and Lake counties and part of St. Louis County (see Figure 1), is underlain by Keweenawan rocks except for a narrow strip along the Canadian border. Early studies of these rocks were made principally by Winchell and by Irving, as shown by the list of publications given below. Because of the size and inaccessibility of much of the region, these early studies were confined to a narrow strip along the shore of Lake Superior. Later Grout and other members of the Minnesota Geological Survey made detailed studies of the Duluth gabbro.[1]

Between the areas covered by these workers lies a region in which only reconnaissance work had been done previous to the mapping presented in this report. It is planned eventually to map in detail this entire area, but as it embraces approximately 4,000 square miles of forested or brushy country, much of it not easily accessible for detailed work, it will take many field seasons to complete the task.

The particular region mapped in this survey was selected because of unusual plagioclase feldspar masses of very high purity, for which it is hoped uses may be found, but the results are also significant as an example of the geology of a great Keweenawan area. The Keweenawan of this region consists almost entirely of igneous rocks, and even the few sedimentary rocks known are closely connected with extrusive igneous activity.

The geologic setting of the area mapped is well shown in Figure 1. It is about centrally located in the Keweenawan area of the north shore of Lake Superior and lies above the thickest part of the Duluth gabbro, but probably is not connected with it by continuous intrusive masses below the drift.

The first geological observations on the north-shore rocks were made by Norwood and published in Owen's report to Congress on the territories of Wisconsin, Iowa, and Minnesota, and extensive observations were later made by Winchell and by Irving. Some of Winchell's notes show that at this very early date he appreciated the true nature of the anorthosite masses. Later Lawson and Elftman made special reports on the anorthosites and recorded many facts regarding their occurrence,

[1] F. F. Grout, "The Pegmatites of the Duluth Gabbro," *Economic Geology*, 13:185–97 (1918); "The Lopolith, an Igneous Form Exemplified by the Duluth Gabbro," *American Journal of Science*, 46:516–22 (1918); "Internal Structures of Igneous Rocks: Their Significance and Origin, with Special Reference to the Duluth Gabbro," *Journal of Geology*, 26:439–58 (1918); "Two Phase Convection in Igneous Magmas," *Journal of Geology*, 26:481–99 (1918); "A Type of Igneous Differentiation," *Journal of Geology*, 26:626–58 (1918).

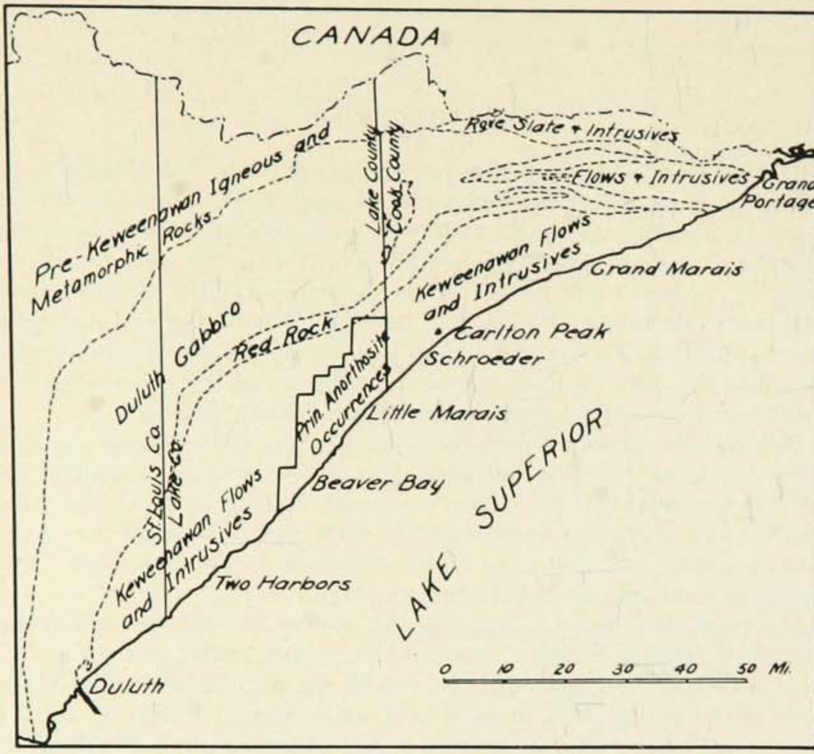


FIGURE 1. — Key map showing general areal geology of northeastern Minnesota and the location of the area with abundant anorthosite (area mapped).

mainly near the shore. They disagreed regarding their origin, as will be brought out in the discussion of the origin of the masses. These and other investigations are noted in the following bibliography. Still others will be referred to by footnotes in connection with more specific problems in the text.

CHRONOLOGICAL LIST OF PUBLICATIONS ON THE GEOLOGY OF THE AREA

1852 Norwood, J. G., in D. D. Owen, *Report of a Geological Survey of Wisconsin, Iowa, and Minnesota*, p. 380. Washington, D. C.

1880 Winchell, N. H., *Preliminary List of Rocks* (Ninth Annual Report of the Geological and Natural History Survey of Minnesota).

1881 Winchell, N. H., *Preliminary List of Rocks* (Tenth Annual Report of the Geological and Natural History Survey of Minnesota).

1883 Irving, R. D., *The Copper-bearing Rocks of Lake Superior* (U. S. Geological Survey, Monograph 5).

1893 Lawson, A. C., *The Anorthosytes of the Minnesota Coast of Lake Superior* (Geological and Natural History Survey of Minnesota, Bulletin 8, Part I).

1894 Elftman, A. H., *The Anorthosytes of the Minnesota Shore of Lake Superior* (Twenty-second Annual Report of the Geological and Natural History Survey of Minnesota).

1899 Winchell, N. H., *The Geology of Minnesota* (Final Report of the Geological and Natural History Survey of Minnesota), Vol. 4.

1900 Winchell, N. H., *The Geology of Minnesota* (Final Report of the Geological and Natural History Survey of Minnesota), Vol. 5.

1903 Clements, J. M., *The Vermilion Iron-bearing District of Minnesota* (U. S. Geological Survey, Monograph 45).

1911 Van Hise, C. R., and Leith, C. K., *The Geology of the Lake Superior District* (U. S. Geological Survey, Monograph 52).

1925 Schwartz, G. M., *A Guidebook to Minnesota Trunk Highway No. 1* (Minnesota Geological Survey, Bulletin 20).

1933 Grout, F. F., "Anorthosite and Granite on Pigeon Point," *Bulletin of the Geological Society of America*, 39:562–63.

1937 Schwartz, G. M., "The Calcic Feldspar Deposits of Minnesota," *Bulletin of the American Ceramic Society*, 16:471–76.

CHAPTER I

GENERAL FEATURES OF THE REGION

Area

The area mapped in detail for this report is approximately 200 square miles. It is made up of blocky units, mostly townships, along the north shore of Lake Superior, which trends N. 50° E. (See Plates 1–6.) The anorthosite masses, which were the principal objects of study, are distributed over a very irregular area.

The southwest edge of the area is at the mouth of the Split Rock River, about eighteen miles northeast of Two Harbors, and at about longitude 91° 25′. The eastern edge is along the Lake-Cook county line, which is the range line between R. 5 and 6 W. of the fourth principal meridian, and at about longitude 91°. The northwest edge is step-like, following township and section lines, but extending to the north town line of T. 59 N. at about latitude 47° 33′.

Culture

The greater part of the area covered in this report is still unsettled, and will no doubt remain so, because of its rough and rocky character. A small portion along the north side is within the Superior National Forest; the remainder is under the protection of the Division of Forestry of the Minnesota Department of Conservation. The inhabitants of the area live mainly along the shore of Lake Superior and in the vicinity of Finland. Beaver Bay, Little Marais, and Finland have post offices and the principal stores, schools, and garages of the district, but there are several smaller stores and refreshment stands at various points. The principal occupations, in addition to caring for the tourist trade, are commercial fishing on Lake Superior, agriculture, and forestry. The growing season is short, which is a considerable handicap to agriculture. The problems confronting the area around Finland have been recently studied and described by D. H. Davis [1] in a most instructive paper.

Practically the entire area was originally covered with a coniferous forest, but this was cut long ago, and most of the area has been burned over so that the forest is just beginning to re-establish itself. Several of the creeks and rivers of the area are well-known trout streams, particularly the Manitou and Caribou and the headwaters of the Baptism and Beaver rivers. The chief game animal is the deer, which is plentiful, particularly in the more level and grassy areas. Moose still live in the

[1] "The Finland Community, Minnesota," *Geographical Review*, 25:382–94 (1935).

wilder and swampy spots at the headwaters of the Baptism, Beaver, and Manitou rivers. Beavers have ponded up a number of the smaller streams.

Travel in the region is mostly along State Highway No. 61, a wide, graded road which skirts the shore of Lake Superior across the entire area. State Highway No. 1 extends northward from near Crystal Bay on Lake Superior toward Ely.

Topography

This region has a characteristic topography, closely related to the rock structure in spite of extensive glaciation, which has modified pre-existing features and left moraines and lake deposits.

In common with most of the north shore of Lake Superior this section of the coast is almost continuously rocky. Occasional small bays and

Figure 2. — Split Rock lighthouse, located on an anorthosite and diabase cliff.

coves have sand and gravel beaches with no rock exposed for some distance back, but commonly the rocks form gently sloping surfaces which rise from beneath the lake, or cliffs which rise abruptly from the water's edge. These cliffs are from a few to a hundred or more feet in height. (See Figure 2.)

In a general way the coast appears straight, especially as shown on a small-scale map. At close range, however, the coast is not straight, but rather closely adjusted to the details of structure and resistance to erosion of the rock units. It should be emphasized that jointing seems to favor erosion. The relatively soft amygdaloidal tops of lava flows also form zones easily attacked by wave action, and many wave-cut cliffs

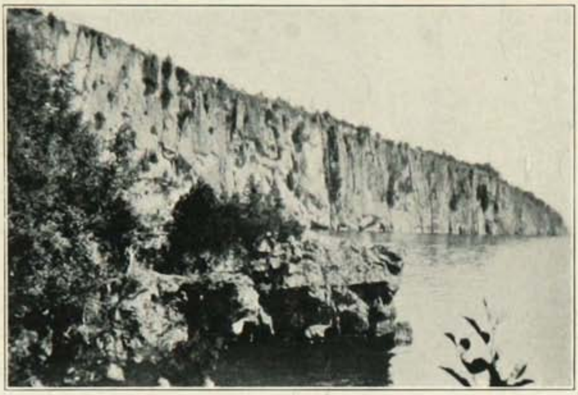


FIGURE 3. — Much-jointed rhyolite, Little Palisades, Lake Superior.

result from undercutting of the more massive jointed rocks overlying such zones.

The coarse-grained intrusive diabases and associated anorthosite masses are the most resistant rocks alongshore and form the bolder parts of the coast; the northeast headland of Beaver Bay and the Split Rock lighthouse cliff (Figure 2) are excellent examples. Farther up the coast toward Two Harbors, Encampment Cliff and Silver Cliff are other examples. Both the Great Palisades, four miles east of Beaver Bay, and the Little Palisades, just east of the Baptism River, are composed of highly jointed rhyolite that has been undercut by wave action, developing high, vertical cliffs. (See Figure 3.)

Where the shore is at an angle to the strike of a series of flows, a

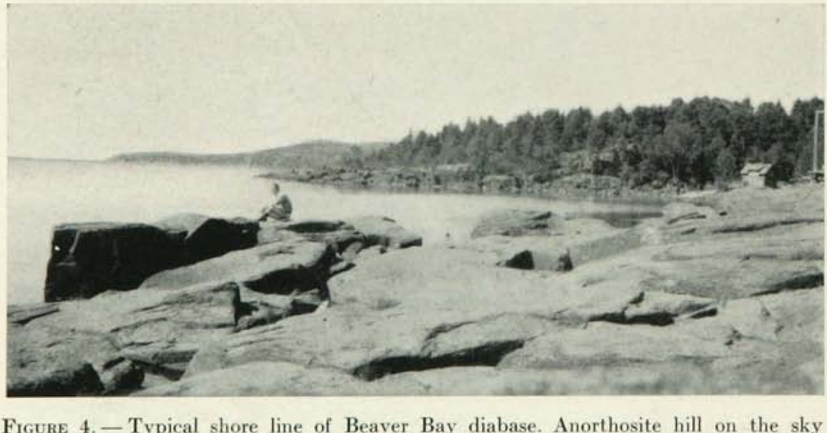


FIGURE 4. — Typical shore line of Beaver Bay diabase. Anorthosite hill on the sky line. The regional dip is indicated by the inclined joint surfaces.

small-scale serrated outline is commonly developed, with an indentation for each amygdaloidal top and a projecting point for each massive center of a flow. This feature is so small, however, that it shows only on large-scale maps. The north coast of Lake Superior has been referred to as a "fault escarpment," but the term is not deserved. The places where the coast line is abrupt are places where cliffs have developed by wave erosion. It is exceptional for these to have any great linear extent, and most of the cliffs or bluffs strike inland along the boundaries of massive intrusive diabase dikes or sills. It is more nearly correct to say that the shore line along the section mapped is marked by wave-cut cliffs interrupting a slope which, both beneath the lake and inland, is fairly well controlled by the regional dip of the rocks. Many of the sills seem to

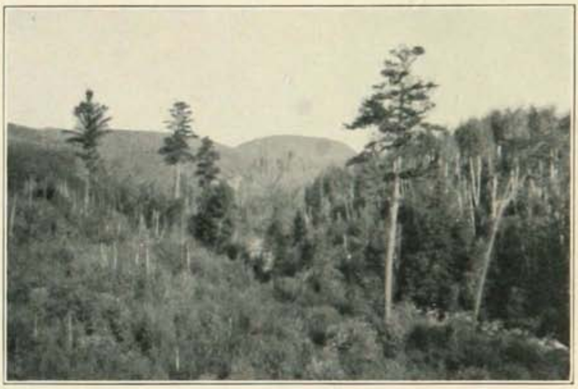


FIGURE 5. — Valley of the Baptism River. Diabase hills in the distance.

be characterized by broad joint planes that dip in the direction of the regional dip, although not necessarily coinciding with it. This gentle slope of the structure toward the lake is evidently the reason why the rock surface slopes gradually from the upland beneath the lake. (See Figure 4.)

In general there is a rather sharp rise from the shore inland for the first mile or two, but this is not at all uniform. Where the region is underlain by diabase, the rise is more continuous and abrupt than where flows form the prevailing rock. The gentle rise in flows is illustrated by the Caribou River valley near the Lake-Cook county line. The flows are usually thin, consequently the rise may take place as a series of saw-tooth monoclinal ridges with escarpments facing north or northwest away from the lake and back slopes toward the lake. The region north of Beaver Bay and east of the Beaver River furnishes a good example of several small, minor saw-tooth ridges formed by the erosion of the flows.

The diabase sills form similar but larger escarpments and back slopes, the most noteworthy being the Beaver Bay diabase sill which extends unbroken from Split Rock to Beaver Bay. (See Plate 1.) Dikes are characteristically marked by bluffs on both sides, but dikes and sills often merge in a manner confusing to the field geologist in such a brushy area, where bird's-eye views are all too few. The high, rugged portions of the area coincide very closely with the diabase intrusives (Figure 5) and associated red rock (granite) facies and with the inclusions of anorthosite.

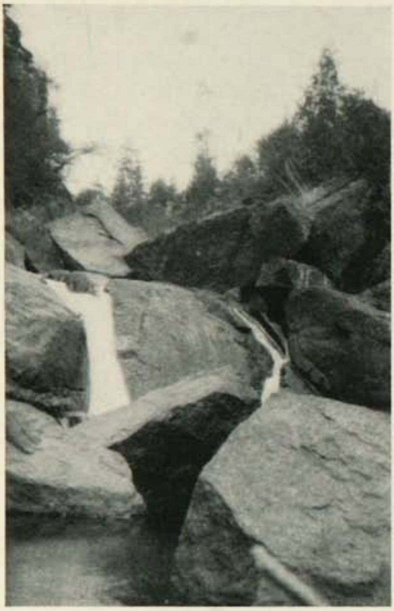


FIGURE 6. — Beaver River at low stage, flowing over diabase talus.

Since the Hudson Bay divide is not far to the north, at places only twelve miles, there is a restricted drainage area for most streams on the north shore of Lake Superior in Minnesota. The streams are therefore small, as is shown by the following data:[2]

River	*Drainage Area*
Split Rock	48 sq. mi.
Beaver	120
Baptism	135
Manitou	71

Five major streams and many minor creeks drain into Lake Superior. The rivers are from west to east: Split Rock, Beaver, Baptism, Manitou, and Caribou. The annual rainfall is about thirty inches, concentrated especially in winter and spring, so that streams are high in spring and relatively low during the remainder of the year. The headwaters of the streams are in the swamps and small lakes of the upland, 600 to 800 feet above Lake Superior; the upper stream courses are meandering and sluggish, and rock exposures are not numerous even in the stream beds. As the streams flow southeast within a few miles of Lake Superior, the gradient steepens, and rock exposures with accompanying rapids and falls become numerous. (See Figures 6 and 7.) For a mile or two near Lake Superior the streams flow over practically continuous outcrops. Many of the streams in their middle and lower courses are controlled by the rock structure, particularly by the attitude of the sills. The streams flow in strike valleys close to the north-facing escarpments of the sills, flows, or dikes — for example, the tributaries of the Beaver, Baptism, and Manitou rivers. (See Plates 1–5.)

The many falls of these streams, for example, Manitou Falls, result from undercutting of soft amygdaloidal zones or from contact of re-

[2] Report of the Water Resources Investigation of Minnesota, 1911–1912 (State Drainage Commission and U. S. Geological Survey).

sistant intrusives with the softer flows. One exception is a falls in the Caribou, which is due to a fault.

It should be emphasized that for the most part the streams occupy valleys which they have not eroded in postglacial time but simply occupied after the lowering of the waters from the stage of glacial Lake

FIGURE 7. — Falls of the Baptism River, flowing over a dike.

Duluth to somewhere near the present level. The master streams have eroded their valleys into bedrock over parts of their courses. Some of the preglacial valleys and gorges are now occupied by two small streams which flow in opposite directions from very low divides. (See Plate 1 for an example.) The preglacial topography seems to have been in a stage between youth and maturity. The area was dissected, but many narrow gorges remained.

CHAPTER II

GENERAL GEOLOGY OF THE REGION

The anorthosite masses of Minnesota are found in a series of Keweenawan rocks which extend from Duluth to Grand Portage Bay. (See Figure 1.) Older rocks are exposed beneath the Keweenawan at Duluth and Grand Portage Bay, but they lie far to the north of the region treated in this report. The nearest exposed rocks older than Keweenawan are fully thirty miles from the area mapped.

It is probably significant that the area of abundant anorthosite and also most numerous and largest diabase intrusives is above the thickest part of the Duluth gabbro. (See Figure 1.)

Keweenawan Formations

A complete series of formation names has not previously been applied to this region. The following tabulation is an attempt to make a logical outline which will preserve some of the names previously used for members.

Table of Formations

Upper Keweenawan (in neighboring areas)	Sandstone and other sediments
Middle Keweenawan	Beaver Bay complex Beaver Bay and other diabases Red granite facies Anorthosites, etc. Keweenaw Point volcanics Basalt and felsite lava flows Local tuffs and sediments
Lower Keweenawan (in neighboring areas)	Puckwunge formation Sandstone Conglomerate

The term "Puckwunge conglomerate" was used by Winchell [1] for the basal Keweenawan conglomerate and sandstone in the Grand Portage region and elsewhere. The term "Puckwunge formation" is here applied as probably intended by Winchell, that is, to all of the sediments beneath the lowest flow. These sediments are not exposed in the region considered in this report, but lie stratigraphically below the rocks described.

[1] *The Geology of Minnesota* (Final Report of the Geological and Natural History Survey of Minnesota), Vol. 4 (1899), pp. 14, 297, 307, 325, 517; *American Geologist*, 20:50–51 (1897).

"Keweenaw Point volcanics" seems the logical name for the great series of Middle Keweenawan flows and associated sediments which are best known as they appear on Keweenaw Point (Michigan) in Lake Superior. A comprehensive series of studies of these volcanics has been made by the United States Geological Survey and the state surveys of Michigan, Wisconsin, and Minnesota. Of these reports only those by Irving [2] and by Van Hise and Leith [3] treat the whole area of exposure of these rocks. Irving used the term Keweenaw series, and Van Hise and Leith the phrase Keweenawan series for the rocks here named Keweenaw Point volcanics. Irving limited his Keweenaw series essentially to the volcanic and associated rocks and some sediments conformably above, using the term Keweenawan series for all Keweenawan rocks, including sediments above, below, and interbedded with volcanics. The term Keweenaw Point volcanics should therefore be applied as a formation name to the flows and associated fragmental rocks included by Irving in the lower division of Keweenaw series and by Van Hise and Leith in the middle division of Keweenawan series. Their two monographs give a sufficient description of the rocks, structure, and correlation to provide the basis for such a formation name.

The term "Beaver Bay complex" is an expansion of the phrase Beaver Bay group as used by Irving and Beaver Bay diabase as used by Winchell. The complex is described in detail later in this report.

Thickness. — The thickness of the Keweenawan rocks on the north side of the Lake Superior geosyncline is as remarkable as that of the better known series on the south side, where the great copper deposits led to intensive studies. A. E. Sandberg [4] has recently published the result of a very careful study of the sequence and thickness of flows from the unconformity above the Huronian west of Duluth to Two Harbors, nearly thirty miles northeast alongshore. He estimates a thickness of extrusives and related sediments of 20,856 feet and of intrusives of 18,626 feet, of which 14,500 feet is Duluth gabbro. This is by no means the maximum thickness, as many flows above those he studied are exposed northeast of Two Harbors; a continuation of measurements in that direction will add considerably to the total.

Inland from Beaver Bay, in the midst of the anorthosite area, it is forty miles to the base of the gabbro. With an average dip of 10°, which is conservative, this would give an indicated thickness of 37,000 feet, of which probably one-half is Duluth gabbro. The structures in the gabbro, however, indicate a much steeper dip, probably close to 25°. Grout,[5] on

[2] *The Copper-bearing Rocks of Lake Superior* (U. S. Geological Survey, Monograph 5, 1883).

[3] *The Geology of the Lake Superior District* (U. S. Geological Survey, Monograph 52, 1911).

[4] "Section across the Keweenawan Lavas at Duluth, Minnesota," *Bulletin of the Geological Society of America*, 49: 795–830 (1938).

[5] "The Lopolith, an Igneous Form Exemplified by the Duluth Gabbro," *American Journal of Science*, 46: 521 (1918).

this basis, has estimated the maximum thickness of the gabbro alone as 50,000 feet. It is probable that the dip gradually flattens from an average of at least 25° near the base of the gabbro to an average near Lake Superior of certainly not less than 10°. An average of 17½° would indicate the total thickness of the north-shore Keweenawan as 66,500 feet.

It is of interest to note that in 1883 Irving[6] suggested that the Keweenawan in Minnesota might reach 24,000 feet, and estimated the thickness of the flows and diabases above the gabbro as 16,000 feet for the Split Rock region. This compares well with the estimate based on a 10° dip, which as indicated above would assign a thickness of 18,500 feet to this series. Sandberg's recent measurements at Duluth suggest that the largest of the above estimates is nearest the truth.

Sediments.—The Keweenawan of the north shore of Lake Superior has remarkably little sedimentary material. At the base, in the Grand Portage area, is a conglomerate called the Puckwunge conglomerate by Winchell.[7] Overlying the conglomerate is a sandstone which has recently been mapped in some detail and is estimated to be 100 feet thick.[8]

Above the oldest known flow, however, practically no thick continuous sandstones are known in Minnesota. Mr. Schwartz worked in the Beaver Bay region daily for two months in the summer of 1931 before finding the first sedimentary rock. Farther east, however, along the Baptism and Manitou rivers and along the lake shore east of Beaver Bay, sandy sediments are somewhat more common.

Flows.—The flows of this area belong to the large Keweenawan series of the Lake Superior region. They are shown by exposures both to the southwest and northeast to be many thousand feet above the base. The flows of the north shore strike inland both near Duluth and near Grand Portage, but in the district covered by this report, between the mouth of the Split Rock River and the Caribou River near the east Lake County line, many flows strike roughly parallel to the shore. However, comparison with the flows on Keweenaw Point suggests that those of the Minnesota coast are stratigraphically below those on the point, since the amount of conglomerate and other sedimentary rocks is very small in the Minnesota exposures, whereas more or less continuous conglomerates occur interbedded with flows on Keweenaw Point from the lowest exposed horizon upward. The base of the Keweenawan there is faulted beyond observation by the Keweenaw fault.

Intrusive Igneous Rocks.—In the early reports by Irving and Winchell distinctions between extrusive and intrusive igneous rocks were not always in accord with modern interpretation, but the large sill between Split Rock and Beaver Bay has always been recognized as an important

[6] *The Copper-bearing Rocks of Lake Superior,* p. 266.
[7] *The Geology of Minnesota,* 4:13.
[8] F. F. Grout and G. M. Schwartz, *The Geology of the Rove Formation and Associated Intrusives in Northeastern Minnesota* (Minnesota Geological Survey, Bulletin 24, 1933), p. 6.

rock mass, and the name Beaver Bay diabase applied to it. There is good reason to believe that all of the intrusives of the area under consideration are closely related, the Beaver Bay diabase being the largest, but otherwise not radically different from the others.

Irving[9] used the term Beaver Bay group, but included in it a heterogeneous series of rocks. He says, "This group is especially characterized by a predominance of black, coarse-grained, olivine-bearing gabbros in very heavy layers without amygdaloids, and by the great abundance and prominence of its included red felsitic porphyries and granite-like rocks. There are, however, very considerable thicknesses included of fine-grained ash bed diabases with and without amygdaloids, while the ordinary fine-grained diabases with amygdaloids are not excluded though they are rarely met with." Winchell[10] used the term Beaver Bay diabase for the large sill extending from Split Rock to Beaver Bay, but referred to it as an extrusive.

The intrusives of the region consist of two main rock types: the diabases, including facies which are typical gabbro; and the red granite (see page 40), which is closely associated with the larger diabase masses but does not necessarily show a gradation to diabase. The possible sharp separation is illustrated by several masses in the area near the Split Rock lighthouse. (See Plate 1.)

In general the diabases form sill-like masses, but detailed mapping usually reveals that the sills are not at all regular, as are related sills in the Rove slate[11] area to the northeast. The lack of regularity is doubtless due to the fact that flows are massive rocks and have much less bedding than have the slates.

Large dikes of diabase branch off from the sill-like masses, for example, on the Beaver River in Sec. 9, T. 55 N., R. 8 W. and south and east of Cramer. (See Plates 1 and 4.) Small dikes a few feet in width occur at many places in the flows where exposures are extensive, for example, on the shore of Lake Superior and along the principal streams.

Pleistocene Formations

Glacial Drift. — No special attempt was made to work out the glacial geology of the region in detail, since it was not important in connection with the main problem. Furthermore, detailed glacial mapping in a region so thickly covered with brush is at best difficult and unsatisfactory. Notes were made on the topography and, where exposed, on the character of the drift. Over much of the area the glacier appears to have been eroding rather than depositing, and the rock hills, particularly the resistant anorthosite masses, have the characteristic rounded form of glaciated rock masses. Back from the shore, however, the north border of the Late

[9] *The Copper-bearing Rocks of Lake Superior,* p. 267.
[10] *The Geology of Minnesota,* 5:63.
[11] Grout and Schwartz, *op. cit.*

Wisconsin Superior Lobe was not far away, the ice was presumably thin and melting, and forward movement nearly balanced melting, so that locally rather typical terminal moraine topography was developed. Some of the best belts are in the area around Finland. These are part of the belt referred to by Leverett as the Highland moraine. The areas of nearly level drift are classified as ground moraine. The drift is gravelly to stony, with a high content of the Keweenawan rocks of the north shore. Diabase, anorthosite, basalt, red syenite, and felsite make up the greater percentage of material, but occasional pebbles of iron formation, granite, and granite gneiss indicate some contribution from the more distant Archean and Huronian rocks. Enough fine material is usually present to make a loamy or sandy soil.

Outwash deposits occur locally, but the broad valley of the Caribou River seems to be the only extensive area of gravel deposits not covered by the red clays of glacial Lake Duluth. It is probable that the broad level area in the northwest portion of T. 55 N., R. 8 W. has outwash deposits beneath the lake clays.

Northwest of the area mapped, drift covers an increasingly high percentage of the region, so that outcrops are few and the structure could not be so well determined as in the area here described.

FIGURE 8. — Folds in varved clay of glacial Lake Duluth, Highway No. 1, Baptism River valley.

Deposits of Glacial Lake Duluth. — Leverett [12] states that in this area the highest shore line of glacial Lake Duluth may be recognized at about 1,190 feet above sea level. In general this beach is not conspicuous, and in the brush it would be entirely unrecognized except by expert glacial geologists. Lower down are many other levels at which the lake halted for a period. Some of these are marked at places by wave-cut cliffs, which are by no means continuous at a given level and seem to depend fully as much on geological factors as on the lake level itself. By this is meant that the variation in hardness of the rocks, character of jointing, and

FIGURE 9. — Concretions from varved clay of glacial Lake Duluth, Baptism River valley.

resistance to chemical weathering usually determined whether or not the waves had an opportunity to cut a cliff. The topography that probably existed in preglacial time, or at least before the Superior Lobe invaded the area, also had much to do with the development of the cliffs.

More easily recognized than the shore line at many places are the characteristic red lake clays. These clays form the prevailing soil of many of the nearly level areas, for example, of Secs. 5, 6, 7, and 8, T. 55 N., R. 8 W. The lake clays are also exposed along most of the stream valleys, where the slump of the plastic material may prevent the establishment of vegetation on the steep slopes. Somewhat disturbed varved clay, with concretions, is well exposed in a road-cut near the Baptism River. (See Figures 8 and 9.)

Along some of the larger streams extensive sand and gravel deposits were formed, possibly partly as delta deposits in the glacial lake. A deposit of highly cross-bedded sand and gravel has been well exposed for

[12] Frank Leverett, *Moraines and Shore Lines of the Lake Superior Region* (U. S. Geological Survey, Professional Paper 154A, 1929).

many years in a roadside gravel pit on the west bank of the Manitou River at Highway No. 61. Very extensive gravel banks are exposed along the Caribou River in Secs. 11, 14, 23, and 24, T. 55 N., R. 6 W.

Structure

The general structure of the district is simple. Most of the flows and sills strike roughly parallel to the shore of Lake Superior, N. 50° E., with an average dip of about 10° toward the lake, in keeping with the location of the area on the north limb of the Lake Superior syncline. Locally the structure may diverge widely from the regional trend, but it is noteworthy that northward dips are rare. (See Plates 1–6.)

Several distinct features show the structures of the rocks. The lava flows show contacts, marked by a change of rock, by amygdaloidal zones, and by ropy surfaces. Rhyolite flows have commonly an internal flow structure (see Figure 16) roughly parallel to the surface, but with much contortion. The flow structure is marked by an alternation of light and dark red layers, with a few gray and green layers at places, and by platy parting. Commonly the parting has resulted in weathering to slabs which are so thin and regular as to be distinguishable from red shale only by careful work with a microscope. Some faint markings appear in certain basalts also apparently parallel to the surface. The sediments with sandy and shaly texture have well-marked bedding and lamination. Intrusive sills and dikes are commonly massive, but the contacts are clearly indicated by chilled margins on dip-slopes and in cliffs. A few of the larger intrusives have bands, schlieren, or flow layers of alternating light and dark colors, which indicate the attitude of the walls, steep if in a dike and dipping gently if in a sill. These are very conspicuous in some of the sills and dikes. (See Figures 23, 24, and 25.) Examples of gently dipping layers occur along the road north of the Finland lookout tower. Examples of vertical layers may be seen east of the Cramer lookout tower, T. 58 N., R. 6 W., and on the bluff one-fourth of a mile west of Nine Mile Lake, T. 59 N., R. 6 W. Near the north edge of the area mapped, in the northwest part of T. 59 N., R. 6 W., is a sill with prominent foliation, suggesting a gentle synclinal structure. The most southerly outcrops have bands dipping northwest at low angles, whereas those in the north dip southeast at angles of 10° to 20°, as is more common in the whole area.

The structures in the anorthosite fragments are noted on pages 51–52, but are unrelated to the larger structures of the region.

As a whole, the structural features are neither numerous nor easily followed from place to place. There are few spots where the rocks are so well exposed or peculiar that key beds can be followed and correlated.

There are frequent references in the literature to a major fault along the north shore of Lake Superior, probably inferred from the relatively straight shore line. During the field work for this report, which involved detailed mapping of twenty-eight miles of the shore line, no evidence of this fault was found aside from the relative straightness of the shore line. All of the structure can be accounted for by the position of the area on the gentle north limb of the syncline and the intrusion of an extensive series of sills and dikes as well as intermediate transgressing igneous bodies. It is probable that the lava flows would have a generally simple structure throughout the entire area if it were not for the disturbance caused by the tremendous amount of igneous intrusive material.

Plate 6 shows (1) the areal distribution of diabase and flows, (2) the dip and strike of the flows and sediments, and (3) to a lesser extent the dip and strike of the bands in the intrusives. The northeasterly strikes are clearly dominant, and the outcrops of two particularly thick and easily recognizable flows are shown to indicate the fact that the general structure strikes northeast. One, a red ophite, is clearly traced for about twelve miles, from Twin Lakes nearly to Little Marais. At places the flows show wide departures in strike, and some in dip, from the general structure. The map (Plate 6) shows that these departures are near the intrusives, especially where diabase forms irregular cross-cutting bodies or dikes. The irregularity of the intrusives is clearly brought out, as is the fact that several large intrusives are essentially sill-like in form.

The best information as to the structure of the flows is obtained along the shore of Lake Superior and along a few of the major streams, where exposures are practically continuous. Along these strips there are contacts and structural relations which would probably never have been suspected if work had been restricted to the scattered inland areas, largely covered with soil. A series of significant exposures along the lake and a series up the Baptism River are noted in the following paragraphs, beginning at the southwest. (See Plate 6.)

In the bay just west of the Split Rock anorthosite masses, the flows strike N. 25° W. and dip 12° E. This is practically at right angles to the prevailing strike, which is shown to the east at Little Two Harbors, where the strike is N. 50° E., dip 9° SE.

At Beaver Bay, where there is a mixture of intrusives and extrusives, a well-banded rock near the west side of Beaver Bay strikes N. 30° W., and dips 8° NE.

Farther east a series of flows are exposed at Silver Bay, with diabase on both sides. The flows and a tuff have a general northerly strike with dips ranging from 8° to 25° E. Beyond the diabase northeast of the bay, the strike and dip are about normal, N. 20° E. and 10° E., respectively.

The structure near the Great Palisades, four miles east of Beaver Bay, is also complicated. The Palisades are due principally to a thick rhyolite flow which overlies a series of basalt flows. (See Figure 10.) Southwest of the Palisades, in NE¼ Sec. 28, T. 56 N., R. 7 W., is a fault with a throw of 10 feet between diabase and red rock. This strikes N. 35° E. and dips southeast. To the northeast, in Section 21, two small faults strike about N. 20° W. and dip 80° W. The flows have a variable strike from north-south to east-west with dips ranging from 10° to 40°, mainly east and south, but so distorted that no general dip can be recognized. Other faults of similar trend occur in the flows at the foot of the southwest end of the Palisade cliff. The three basalt flows exposed beneath the big rhyolite flow all dip easterly with a strike nearly north. The lower contact of the rhyolite is not visible, as it is covered by talus, but prominent eutaxitic rhyolite has layers conforming to the attitude of the basalt flows. Irving noted a 60-foot vertical dike at the east side of the Palisade.

FIGURE 10. — Two basalt flows below rhyolite of the Palisades, Lake Superior.

Northeast of Palisade cliff and near the mouth of the Baptism River the strike is about normal, but the dip is abnormally high, especially along the river. At the Little Palisades, just east of the Baptism River, the strike is again nearly north-south, and for two miles beyond this point there is a great irregularity of dips and strikes in an area with small intrusives. It is doubtless significant that where the strike is prevailingly northerly, the shore line also turns sharply north. Along the shore of Lake Superior near the southwest corner of Sec. 1, T. 56 N., R. 7 W., a series of fourteen flows strike nearly east-west and dip 65° north in contrast to the regional dip of 10° to the southeast.

In Sec. 30, T. 57 N., R. 6 W., just west of Little Marais, there is a local disturbed zone in the southwest quarter of the section. On shore volcanic tuff and breccia are well developed, with fragments up to 10 inches. On one side of a small cove the strike is N. 20° E. and the dip 8° SE.; on the other side the strike is east-west and the dip 5° to the south. The breccia is in contact with massive basalt along a shear zone with a dip to the south of 45°. North of the road at a falls in the small creek in Section 30, an amygdaloidal zone strikes N. 20° E. and dips 80° SE. A sediment or tuff near by has a north-south strike with a 75° dip to the east. Throughout the eastern half of Section 30 the dip and strike are normal, as is also true east of Little Marais, where a number of flows are well exposed. A single thick flow of basalt with closely spaced joints (see Figures 11 and 12) extends from the small creek east of Little Marais northeast almost to the mouth of the Manitou River. The strike averages about N. 35° E. with dips ranging from 10° to 20° SE. Beyond the mouth of the Manitou River the same flow reappears, with only minor variations in dip and strike. It extends to Pork Bay and probably

FIGURE 11. — Columnar jointing in a thick flow of basalt, shore of Lake Superior, near the mouth of the Manitou River.

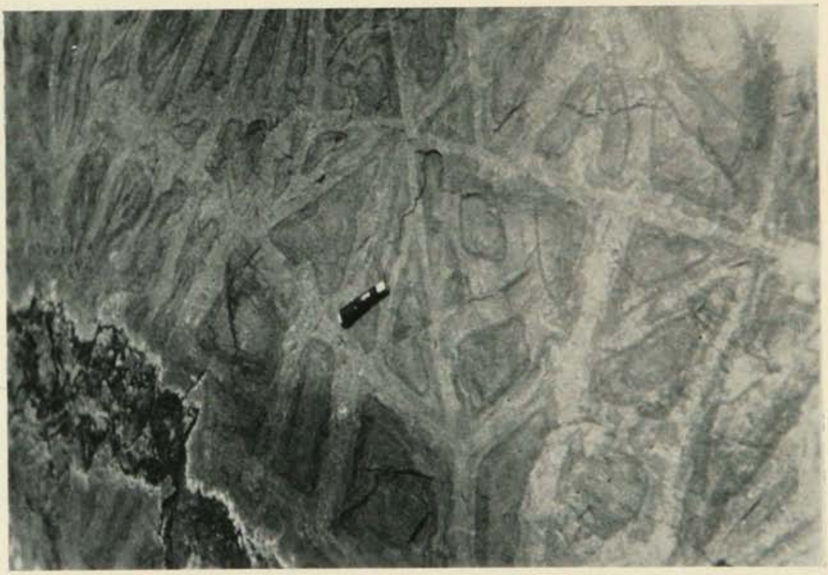


FIGURE 12. — Concentric weathering related to joints in basalt, shore of Lake Superior, near the mouth of the Manitou River.

FIGURE 13. — Contact of two flows, the Palisades, Lake Superior.

FIGURE 14. — Bent pipe amygdules at the basal contact of a flow, showing direction of flow. Shore of Lake Superior, Little Marais.

beyond the Caribou River and the Cook County line, where the mapping for this report was discontinued.

A traverse up the Baptism River for two miles from its mouth shows about twenty successive flows with some interbedded sediment and scattered dikes and sills. So little of the strip is concealed that the structure and succession are probably not much affected by faulting. Still other flows crop out farther up stream, so that it is very certain that there are in the area considerably more than twenty-five flows in series. The other rivers are in similar rocky gorges. The attitudes of the flows at present

FIGURE 15. — Columnar jointing in Beaver Bay diabase, Highway No. 61, near Split Rock lighthouse.

are clearly indicated by the amygdaloidal zones and ropy surfaces between flows. (See Figures 13 and 14.) Most of them dip gently toward Lake Superior and strike nearly parallel to the shore, but locally near the large intrusives the structure is greatly disturbed. The local bunchy forms of rhyolite flows, and the tendency to a rolling surface of even the basalt flows, account for some of the irregularity in the observed structures. There are basalt dikes also, up to a few feet wide, cutting both flows and sills. Some form wall-like points on Lake Superior and others hold up waterfalls on the rivers.

Structure is well shown by a thick porphyritic flow back of the lakeshore outcrops north of Split Rock in T. 55 N., R. 8 W. This flow forms a rather diagrammatic monoclinal ridge with a gentle back slope. The strike seems to change as the ridge continues northeast to the Beaver River. Close to Split Rock it strikes nearly north, but along the east branch of Beaver River there are dip-slopes and amygdaloidal beds striking practically due east.

Jointing is a prominent feature of many of the diabases and basalts of the region. Columnar joints of a rude type are common. (See Figures 11, 12, and 15.) A blocky type of widely spaced joints is characteristic of much of the diabase. (See Figure 4.) The rhyolites are much jointed; in the thickest rhyolite flow this results in high cliffs where waves undercut the joints. (See Figure 3.)

CHAPTER III

DETAILED DESCRIPTION OF KEWEENAWAN FORMATIONS

Basalt Flows

The earliest of the formations in this district are the surface volcanics, mostly basalt flows. They extend far outside the area, from Duluth to Grand Portage along the north shore of Lake Superior and probably from Stillwater, Minnesota, to Keweenaw Point on the south side of Lake Superior. They form the structural foundation of the district, and their general lakeward dip guided many of the intrusives that came later.

The cross sections afforded by the river gorges show to the best advantage the series of flows and their attitudes, and the rocky shores of Lake Superior add some details. (See pages 18–24.) The flows range in size from the large ophite, perhaps 200 feet thick and 12 miles long, down to some that pinch out and disappear in an amygdaloidal streak.

Petrographically the basalts are of several kinds, and nearly all, where well exposed, grade up to fine-grained tops full of amygdules. At a few points amygdaloidal dikes, probably related to the amygdaloidal tops of some local flow, cut through some of the flows or parts of flows already solidified. The compact central parts of flows are commonly brown from alteration, black when fresh, and green if more chloritic than average. Locally the ropy top surface and other parts are bright red. Samples were taken to determine whether there are flows intermediate in composition between basalt and rhyolite, but none was found, and they must be very rare if they do occur in the series. In the tests of Keweenawan flows in the state, some twenty-five have been analyzed chemically; three felsites have over 67 per cent silica, whereas nearly all of the basalts have less than 56 per cent silica; and only two rocks, probably somewhat altered, have intermediate silica. No new analyses of basalt have been made for this report, but the composition of brown basalt at Little Two Harbors is reported in Table 1, No. 154 (page 32).

The petrographic varieties so long distinguished in the Keweenawan flows of Michigan[1] are all well represented in the area — ophites, porphyrites, and melaphyres, all of which may be amygdaloidal and not easily distinguished in the upper parts.

The porphyrites have phenocrysts of plagioclase, the ophites have a mottling which results from large augite grains filled with laths of plagioclase (diabasic texture), and the melaphyres are more uniformly

[1] B. S. Butler and W. S. Burbank, *The Copper Deposits of Michigan* (U. S. Geological Survey, Professional Paper 161, 1926).

fine-grained, showing neither phenocrysts nor mottling. The thick flows are as coarse and diabasic as the smaller sills, and several were described by Winchell as diabases.[2] The characterization of diabasic flows as "ophites" is a matter of convenience, based on the fact that they have an origin and a form different from those of the petrographically similar diabase sills.

The common primary minerals are labradorite, augite, olivine, and magnetite. Quartz is lacking except in amygdules and as rare disseminated secondary grains. The finer, chilled facies have an altered glassy matrix. Augite and olivine are commonly altered to chlorite and serpentine, respectively, but confused aggregates occur. Winchell described a variety of zeolites, agates, epidote, chlorite, quartz, calcite, and other minerals from the amygdules and reported several chemical analyses.[3] Kaolinization and oxidation of iron minerals to hematite are especially prominent in the amygdaloidal layers on the shore of Lake Superior.

The flows were apparently derived from a general reservoir of Keweenawan igneous magma, but the processes by which the basalt was separated from rhyolite are not clear. All the flows are attributed to Middle Keweenawan time and correlated in a broad way with those on the south side of Lake Superior.

Where the basalt flows have been intruded by the diabase, they are more or less contact-metamorphosed, as are other rocks intruded by gabbro and diabase in Minnesota[4] and elsewhere. They become hard and fresh in appearance as a result of the baking by the intrusives, forming hornfelses with a granular, sugary (granoblastic) texture. In regard to the freshened appearance, it should be noted that most of the Keweenawan flows of the region are considerably altered by hydrothermal processes. A really fresh basalt is a rare occurrence in the Minnesota flows except near contacts of intrusives.

Microscopically, the contact rocks are characterized by rounded grains of pyroxene, magnetite, ilmenite, and olivine. Plagioclase forms a mosaic of anhedral to subhedral grains, corresponding in size to the pyroxenes but not rounded in outline to the same extent. Winchell[5] referred to these rocks as "granulitic," but noted that they resemble the contact rocks of the Duluth gabbro. Perhaps the most conspicuous effects are found in the metamorphosed amygdaloidal zones. The amygdules are recrystallized, the typical hydrous fillings, mainly zeolites, being altered

[2] *The Geology of Minnesota* (Final Report of the Geological and Natural History Survey of Minnesota), Vol. 5 (1900), pp. 228–29.

[3] *Ibid.*, Vol. 5.

[4] See G. M. Schwartz, "The Contrast in the Effect of Granite and Gabbro Intrusives on the Ely Greenstone," *Journal of Geology*, 32:89–138 (1924); F. F. Grout and G. M. Schwartz, *Geology of the Rove Formation and Associated Intrusives* (Minnesota Geological Survey, Bulletin 24, 1933); F. F. Grout, "Contact Metamorphism of the Slates of Minnesota by Granite and by Gabbro Magmas," *Bulletin of the Geological Society of America*, 44:989–1040 (1933).

[5] *The Geology of Minnesota*, 5:186, 197.

to various anhydrous minerals — pyroxene, feldspar, quartz, carbonate, magnetite, and epidote. The quartz forms a fine mosaic of interlocking grains, and feldspar forms granular aggregates. The pyroxene and magnetite show the usual rounded form. Not enough data are available to outline the paragenesis of the recrystallized minerals in the amygdules, but it seems clear that a zone of pyroxene grew around many of the amygdules, a mosaic of plagioclase filling the center.

Rhyolite and Felsite Flows

The chief occurrences of rhyolite are in the flows of the Great Palisades and Little Palisades along the shore of Lake Superior, but there

Figure 16. — Flow structure in rhyolite, two miles northeast of Beaver Bay.

are extensions of these areas inland, also a few separate areas. There are good exposures on both flanks of the dike ridge of diabase which runs north past Cramer near the east line of Lake County.

The rhyolites do not present as good evidence of the structure of the region as do the basalts. They are not exposed in long, narrow belts, but in local thick masses. It seems, as has often been suggested elsewhere, that the rhyolite magma was very viscous when it reached the surface (see Figure 16), and probably piled up in thick flows of no very great lateral extent. These might be surrounded and perhaps buried under later basalts.

The bluff of the Great Palisades was described by the earlier survey [6] and no further detail need be added. The rhyolite mass rises abruptly

[6] *Ibid.*, 4:311.

315 feet above the lake, 210 feet in a vertical cliff at one place. No sequence of flows of rhyolite could be clearly distinguished here, though several joints divide the cliffs into steps. That the rhyolite is part of the series of Keweenawan lavas can be clearly seen in the cove at the west end of the Palisades, where rhyolite lies over the basalt flows and some minor sediments in normal attitudes. Nearly all the siliceous flows weather pink, and the joints and parting make it difficult to trim good hand specimens. Weathering results in a rubble of angular blocks and plates a few inches in diameter.

The only minerals commonly visible in the field are corroded phenocrysts of quartz and pink or white feldspars, or both. Dark minerals are very inconspicuous, and in a few exposures all the minerals are too fine to be recognized without the microscope. A few spherulites and lithophysae show that the groundmass was once glassy, though now devitrified. There may have been some flows that were originally holocrystalline and possibly even graphic, but the signs of glassy originals are so numerous that it is likely all had glassy groundmasses.

The microscope shows further evidence of the originally glassy nature of the groundmass. There are perlitic cracks as well as bands of spherulites. Most of the groundmass is now a fine-grained mixture of quartz and dusty red feldspars in cryptocrystalline aggregates, which evidently resulted from devitrification. In this the feldspars, though very minute, show more tendency to be euhedral than the quartz which commonly surrounds them. Fairly large areas of quartz extinguish at one time, but are so filled with dusty feldspars that a casual glance might give the impression of many grains of quartz no larger than the feldspar. Near large quartz phenocrysts some of the quartz of the groundmass is oriented by growth on the phenocrysts.

Besides quartz and dusty feldspars with low indices of refraction, the rocks contain augite (diopside), magnetite, hornblende, apatite, secondary chlorite, leucoxene, kaolinite, and hematite. Rutile was reported by Winchell.[7] The bands so conspicuous in some of the rocks appear in thin section to be coarser and more quartzose than the main part of the rock, but probably this character developed during devitrification from some original difference, such as bands of spherulites or stony layers in an original glass.

The feldspars are so dusty with kaolinite and hematite that accurate identification is difficult and twinning is obscured. Most are zoned, with the outside redder and dustier than the center. Indices of refraction indicate oligoclase, and analyses show that both soda and potash are abundant. Most of the feldspars may be zoned potash oligoclases or, if glassy and clear, anorthoclases.[8] Rarely, near anorthosite inclusions, the rhyolite may have xenocrysts of more calcic gray plagioclase. The rhyolite is

[7] *Ibid.*, 5:220.
[8] *Ibid.*, 5:214.

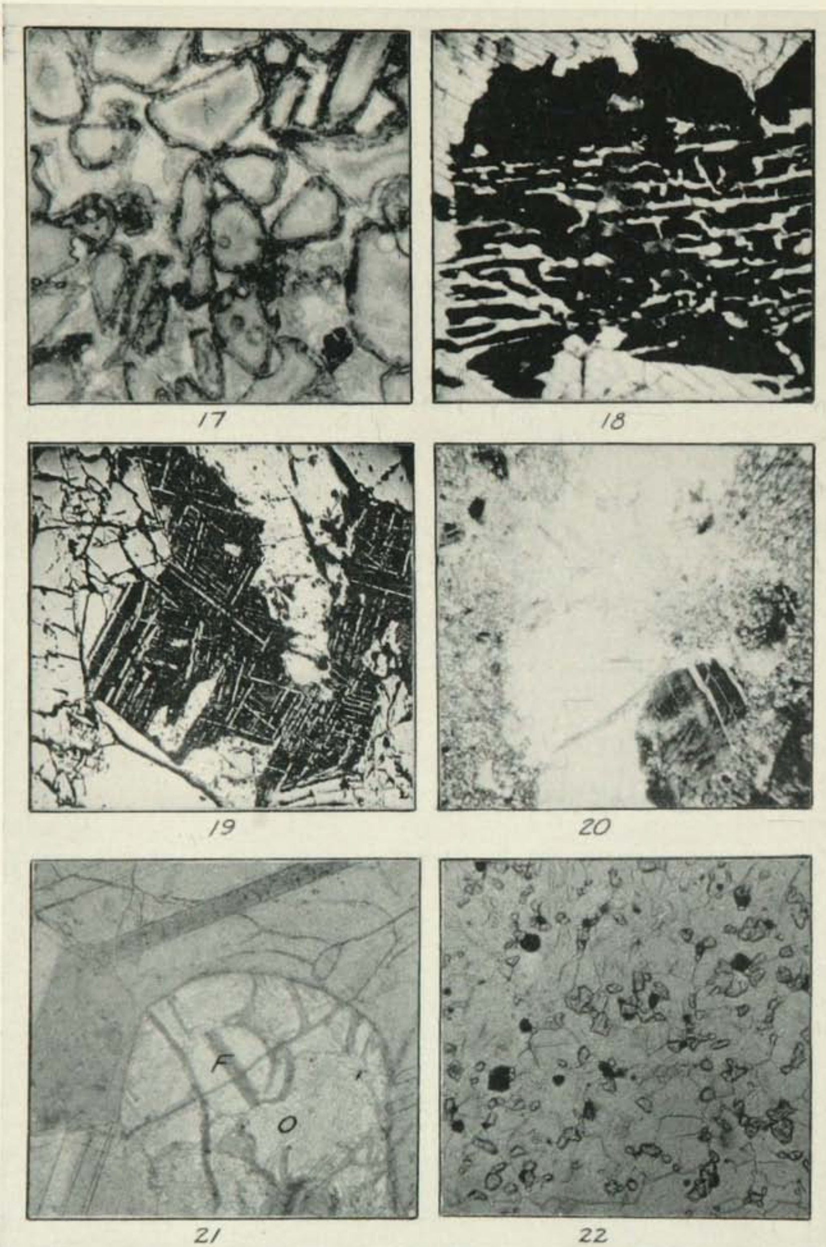
commonly crossed by quartz and chalcedony in veins and breccia zones. Calcite replaces some of the feldspars and is associated with quartz in small veins. This type of rock is commonly called a devitrified porphyritic to felsitic rhyolite in hand specimen, but microscopic study suggests the term aporhyolite, and some early workers used the terms granophyre and micropegmatite to describe the rock.

Besides a certain amount of devitrification and weathering, the chief alteration noted in the rhyolite is in local spots near contacts with later intrusive diabase. Where the heat of the diabase was very great or the rhyolite mass was small and surrounded by the basic magma, the changes are noteworthy and have caused considerable confusion. Along the shore of Beaver Bay the changed rocks are especially well exposed, and it seems clear that the heat of the diabase magma first recrystallized the rhyolite to make it look granitoid on casual inspection and in extreme cases melted it[9] so that it intruded diabase and anorthosite in small dikes, crystallizing as an intrusive red granite. Masses as much as a foot across at Beaver Bay have been transformed to coarse spherulites in groups two or three inches wide, much coarser than any seen in unaltered rhyolite flows. Evidences of similar recrystallization were found at several other places, but not as well exposed. Most of the rhyolite magma seems to be best attributed to a deep source comparable to the source of the more numerous basalts.

Tuffs and Sediments Related to the Keweenaw Point Volcanics

Most of the sediments and fragmental rocks of the area are loosely consolidated and so easily eroded that outcrops are few. There are probably many beds of such rocks concealed in the valleys under debris. At a few points on the shore of Lake Superior a hard rock may have protected some beds from erosion, but in the area mapped few fragmental rocks were seen along the shore, except rhyolite breccias and so-called amygdaloid conglomerates, probably not transported very far. The rhyolite east of the mouth of Baptism River is a breccia of explosive igneous origin with a matrix of fine rhyolite fragments; that in the west end of the cliff of the Great Palisades is a breccia formed from a rhyolite flow, shattered and cemented by quartz and chalcedony. The basaltic material near the center of Sec. 26, T. 58 N., R. 7 W. is an eruptive breccia, showing conspicuous fragments on weathered surfaces, but not so clearly where freshly broken. A breccia or conglomerate in the old railroad cut in Sec. 32, T. 59 N., R. 6 W. contains boulders of diabase and rhyolite, but the exposures are not sufficient to allow determining the origin and relations of the rock. Basalt breccia or conglomerate outcrops around the mouth of the Manitou River and at places northeast for a mile. The

[9] See N. H. Winchell, *The Geology of Minnesota*, 4:301. Compare J. W. Judd, "On Inclusions of Tertiary Granite in the Cuillin Hills, Skye," *Quarterly Journal of the Geological Society of London*, 49:175 (1893).



FIGURES 17–22. — Microphotographs of various rocks of the anorthosite region.

FIGURE 17. — Tuff of green vesicular basalt glass fragments. x22. FIGURE 18. — Graphic intergrowth of ilmenite and silicate. x66. FIGURE 19. — Ilmenite blades forming a lattice in magnetite, which is etched black. x132. FIGURE 20. — Brecciated anorthosite. x66. FIGURE 21. — Inclusions of olivine (O) in feldspar of anorthosite mass. Note inclusion of feldspar (F) in olivine. x66. FIGURE 22. — Inclusions of magnetite (black) and pyroxene in anorthosite, Beaver Bay. x66.

minerals of these breccias are like those of the flows of rhyolite and basalt, but the matrix of some is partly glass, more or less altered, and the cement of some is calcite. The basalt has a large amount of finely disseminated magnetite and ilmenite.

About half a mile above the mouth of the Baptism River, in Sec. 15, T. 56 N., R. 7 W., at a bend in the river, a conglomerate grading to shaly sandstone is exposed for several rods in a bank several feet high. Most of the pebbles are subrounded, are two or three inches in diameter, and are loosely cemented. They are largely of the rhyolite and basalt characteristic of the flow series. The associated sand is largely of opaque red grains, which are believed to have formed by alteration of a basic tuff. There is some calcite in the cement. An analysis of the sediment along the banks of Baptism River is given in Table 1.

The alteration of basalt tuff to a reddish sandy material, mentioned above, is clearly indicated by exposures in Sec. 28, T. 57 N., R. 7 W. In a series of exposures of flows and breccias of volcanic origin there is a bed of cross-bedded fragmental rock about five feet thick. Its color is green, but where most weathered it has turned red and very closely resembles the opaque red sands of the Keweenawan bedded rocks. Several thin sections were made, and the cement was separated and examined. The textures are shown in Figure 17. There are clearly fragments of vesicular green glass which, though altered, are still isotropic. The alteration has resulted in zones of different colors parallel to the original boundaries of grains, so that the structures now somewhat resemble oölites.[10] The cement between the granules has a much lighter color. It is isotropic, has an index of 1.484, and gives a silica jelly on evaporation in hydrochloric acid. These characteristics indicate analcite. Altogether the rock is a rare combination.

Among the flows of basalt there are red to brown beds and dikes of clastic material of another type. Apparently the flows cracked to form open joints, and it is probable that in the upper amygdaloidal zones there were some lava caves that did not wholly collapse for a time. Into these openings there was probably washed the fine basaltic debris from tuffs or the fragments of eroded basalt surfaces. The result is a red-brown, sandy, shaly rock. Microscopically the fragmental texture is clear, even when the rock is fracture-filling and associated with introduced zeolites or carbonate. It closely resembles the altered red-brown tuffaceous beds and the finer matrix of conglomerates. An analysis is given in Table 1, No. 161A. Winchell adopted Wadsworth's term, clasolyte,[11] for an occurrence about three miles west of Little Marais. The clastic grains are partly quartz and partly plagioclase; some of the grains are angular and others rounded. There is a little chlorite, and the whole is much stained with iron oxides.

[10] These forms, colors, and structures are reminiscent of those of the greenalite of the Mesabi Range and recall the contention of Winchell that the Animikie iron-bearing formation was of volcanic fragmental origin. *The Geology of Minnesota*, 5:961, 990–99.

[11] *Ibid.*, 5:461.

TABLE 1.— ANALYSES OF ROCKS AND MINERALS FROM THE ANORTHOSITE AREA
(C. F. Sidener, Analyst)

	155	156	157	158	159	160	161A	85	86	154
SiO_2	71.15	71.99	73.28	76.68	69.66	66.72	50.31	62.73	47.25	52.54
Al_2O_3	12.40	12.36	11.83	12.14	11.49	7.41	14.17	13.69	24.78	13.50
FeO	0.75	0.56	0.56	0.52	0.60	0.69	1.09	1.75	0.48	15.35
Fe_2O_3	5.21	4.99	4.61	3.16	3.95	10.13	10.96			3.60
MgO	1.13	0.72	0.36	0.26	0.71	4.06	5.86	0.65	0.71	3.73
CaO	1.90	0.85	1.04	0.25	2.64	3.10	8.44	5.87	1.23	6.51
Na_2O	1.70	0.99	1.66	1.06	1.15	0.86	0.90	1.83	15.05	1.10
K_2O	2.40	2.45	4.50	3.53	1.08	0.42	0.46	0.68	traces	0.37
H_2O-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H_2O+	2.12	2.92	1.82	1.66	8.55	5.32	7.63	12.25	10.37	3.34
Total	98.81	97.83	99.66	99.26	99.83	98.71	99.72	99.38	99.87	100.04

155 (Rock 124). Purplish red granite, from west bluff at entrance to Beaver Bay. Thirteenth Annual Report of the Geological and Natural History Survey of Minnesota (1884), p. 100.
156 (Rock 127). "Gray quartzite," rhyolite, from the mouth of Beaver River, Beaver Bay. *Ibid.*
157 (Rock 134). Red granite, from the third island below Beaver Bay. *Ibid.*
158 (Rock 139). Rhyolite porphyry, bulk of the Great Palisades. *Ibid.*
159 (Rock 140). Red, laminated or "streamed" rhyolite, from the base of the Great Palisades. *Ibid.*
160 (Rock 149). Red shaly sandrock, associated with conglomerate, half a mile below the first falls of Baptism River. *Ibid.*
161A (Rock 161). Brown heulandite, crystalline vein in traprock, from the town line between R. 5 and 6 W. on Sec. 36 east of Pork Bay. *The Geology of Minnesota,* 5:229.
85 (Rock 634A). Zeolitic mineral, from the shore west of Little Marais, Sec. 29, T. 57 N., R. 6 W. Eleventh Annual Report of the Geological and Natural History Survey of Minnesota (1882), p. 171.
86 (Rock 637A). Thin zeolite seams in feldspar masses, from Beaver Bay. (Natrolite.) *Ibid.,* p. 172.
154 Brown conchoidal basalt rock, from Little Two Harbors. Thirteenth Annual Report of the Geological and Natural History Survey of Minnesota (1884), pp. 100–02.

At the north side of west Twin Lake is an outcrop of sediment that may be more like a graywacke than the more common tuffaceous sediments of the area. It occurs under a bluff of diabase and weathers out to a talus of slabby fragments. The subrounded sand grains are about 60 per cent plagioclase and 25 per cent magnetite, with smaller amounts of quartz, chert, epidote, and kaolinite. There are also fragments of diabase. The bedding is marked in thin section by different sizes of grains. Some of the magnetite is disseminated as if in sand grains, but there is also some in streaks, which may have been introduced.

DIABASES AND RELATED INTRUSIVES

The diabases and related basic rocks of the Beaver Bay complex form the largest exposures in southern Lake County. Because of their resistance to weathering and erosion they form ridges and bluffs up to 300 feet high. Those intrusives that follow the structure, dipping toward Lake Superior, form northward-facing escarpments and more gentle back slopes, but the transgressive and dike-like masses may form high bluffs facing in other directions. The Beaver Bay diabase itself, the best known mass in the group, is sill-like (Plate 1) with minor irregularities and several petrographic facies. Dikes may be illustrated by the ridge south of the creek northeast of Moose Lake, and by the ridges east of Cramer, where two dikes seem to join in a ridge half a mile wide. Probably there are several masses which are intermediate or slightly transgressive or gradational from dikes to sills. A great number of small trap dikes are probably related. The structural setting proves to be more complex than was implied in the old reports of a "Beaver Bay sill." An attempt to interpolate between the outcrops of diabase on the map, on the basis of structural data, shows that most are connected, and it is not unlikely

FIGURE 23. — Vertical banding in diabase, near W¼ cor., Sec. 10, T. 55 N., R. 8 W.

that all are connected underground, if not at the rock surface. Diabase probably forms continuous belts from Wanless in T. 60 N., R. 6 W. southwest nearly to Beaver Bay. A narrow belt of flows along the Beaver River in the south part of T. 56 N., R. 8 W. almost separates the sill at Beaver Bay from this northern area, but it is possible that the diabase breaks through even this in Sec. 26, T. 56 N., R. 8 W. The contacts of many intrusives are so clearly exposed that their sill-like or dike-like forms can be closely determined. The topographic expression and internal structure confirm this interpretation.

Several of the intrusives are conspicuously banded in outcrop, with layers or schlieren of different mineral concentrations in alternation. (See Figures 23, 24, and 25.) There are also many inclusions of gabbro, anorthosite, amygdaloid, rhyolite, and other rocks. Some anorthosites are remarkably large and are described under a later heading (pages 46–63). Part of

FIGURE 24. — Banded troctolite, SE¼ SW¼ Sec. 21, T. 58 N., R. 7 W.

the banded structure may be attributed to contamination of a moving magma by a variety of earlier rocks. Most of the bands, however, are believed to be a result of segregation.[12]

Most of the large dikes and sills are dark-colored, coarse rocks, much coarser than the typical dolerite of thin sills. From this the texture grades to basaltic at chilled contacts. The fabric is diabasic in large part, but certain facies are porphyritic and others granitoid. Near contacts there are dikes and bunches of pegmatitic facies. The Duluth gabbro, a few miles north, has a similar variety of textures but not much porphyry. The coarse ophitic diabase along Highway No. 61 west of Beaver Bay has augite spots up to three or four inches across, but the more common sizes are about one inch. (See Figures 26 and 27.)

The different mineral proportions in the several facies of the intrusives affect the textures a little. Rocks low in feldspar have a granitoid texture, those with about 50 to 75 per cent feldspar are commonly diabases. In rocks with over 75 per cent feldspar the fabric is modified, but the augite, if present, still fills angular spaces between the euhedral feld-

[12] The alternation shows both gradation and abrupt changes, as in varved sediments. (See Figure 24.) Probably several such structures are known in other parts of the world. See J. W. Peoples, "Gravity Stratification," *Report of the Sixteenth Session, International Geological Congress* (1936), 1:360, Plate 2A; A. Geike, "On the Relations of Acid and Basic Rocks: Hebrides," *Quarterly Journal of the Geological Society of London*, 50:230, Plate XIII (1894); and J. R. Cooper, *Geology of the South Half of the Bay of Islands Igneous Complex* (Newfoundland Department of Natural Resources, Bulletin 4, 1936), p. 32.

spars. If feldspar and olivine are the chief minerals, the texture may be granitoid, or the olivine may grow large and enclose feldspars poikilitically.

The basic intrusives may be divided into several petrographic facies, quite aside from the gradation to red granite near their upper parts. (See pages 40–43.) Chemical analyses of several facies are given in Table 2. The diabase may be doleritic (of medium grain), or fine (basaltic), or

TABLE 2. — ANALYSES OF DIABASES FROM THE MINNESOTA COAST OF LAKE SUPERIOR, NEAR BEAVER BAY

	1	2	3	4	5	6
SiO_2	48.77	45.84	46.94	46.88	63.18	50.86
Al_2O_3	18.25	11.19	11.87	20.98	13.27	15.72
Fe_2O_3	2.25	4.02	4.66	3.32	4.03	9.77
FeO	8.44	16.39	11.33	5.56	4.42	2.48
MgO	4.94	3.66	5.99	4.74	1.62	3.55
CaO	10.81	8.39	10.88	11.15	2.74	10.52
Na_2O	2.77	2.68	2.26	2.49	3.47	3.89
K_2O	.45	.83	.48	.29	3.57	.90
H_2O+	.84	.87	.64	1.45	1.20	2.53
H_2O-	.45	.45	.63	1.59	.40	
TiO_2	1.52	3.44	3.86	1.11	1.51	
P_2O_5	.24	1.74	.17	.15	.31	
CO_2				.12		
S		.04		.02		
SO_3						
MnO	.15	.27	.24	.12	.12	
Total	99.88	99.72	99.95	99.97	99.84	100.22

1. Mottled diabase, from Highway No. 61, SW¼ SW¼ Sec. 28, T. 55 N., R. 8 W., R. B. Ellestad, analyst.
2. Diabase gabbro, from Highway No. 61, SW¼ SW¼ Sec. 14, T. 55 N., R. 8 W., R. B. Ellestad, analyst.
3. Diabase with olivine spots, from the shore of Lake Superior, SE¼ SW¼ Sec. 6, T. 55 N., R. 7 W., T. Kameda, analyst.
4. Diabase, from the bluff opposite Encampment Island, Sec. 12, T. 53 N., R. 10 W., S. Goldich, analyst.
5. Intermediate rock, SE¼ SE¼ Sec. 8, T. 57 N., R. 7 W., R. B. Ellestad, analyst.
6. Diabase, from east of Baptism River, J. A. Dodge and C. F. Sidener, analysts, Fifteenth Annual Report of the Geological and Natural History Survey of Minnesota (1887), p. 423.

coarsely mottled (ophitic). Locally, especially near inclusions and red granite, there are coarse pegmatite gabbros. An especially dark facies may be seen in extensive exposures along the highway about a mile southwest of Beaver Bay. At other places there is a gradation by increase of feldspar to some very light rocks, almost anorthosite; but no evidence of aggregations of phenocrysts such as might form anorthosite, as in the sills intruding Rove slates.[13] In several sills, or large parts of them, the augite content is so low that the rocks are troctolite; that is, they contain only plagioclase and olivine, or these with a little magnetite and

[13] F. F. Grout and G. M. Schwartz, *Geology of the Rove Formation and Associated Intrusives* (Minnesota Geological Survey, Bulletin 24, 1933), p. 38.

ilmenite. Troctolites range from peridotites about 90 per cent olivine to anorthosites with 90 per cent feldspar, thus from very dark to very light rocks.

The specific gravities have been tested for only a few facies. The chilled basal margin of the diabase below Split Rock lighthouse has a gravity of 2.921 ± 10 where there are inclusions of light anorthosite. Other facies range from 2.89 to 3.15.

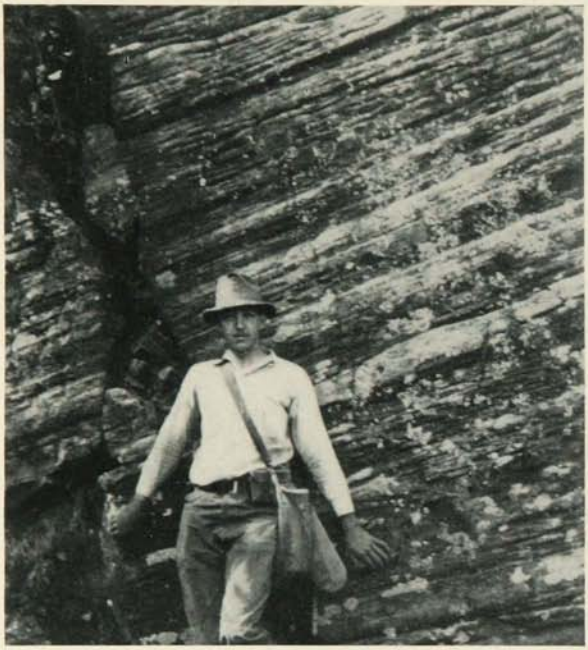


FIGURE 25. — Banded troctolite, SE¼ SW¼ Sec. 21, T. 58 N., R. 7 W.

The minerals of these several facies do not need separate listing and are here listed for the whole group of basic intrusives. They are such as would be expected: essentially basic plagioclase, augite, olivine, magnetite, and ilmenite. Several have primary biotite; hypersthene is less common. Apatite is the only common accessory. Much of the rock is fairly fresh, but the easily attacked olivine is probably somewhat attacked in all specimens. Common secondary minerals are chlorite, serpentine, talc, zeolites, sericite, hornblende, epidote, leucoxene, kaolinite, the several iron oxides, and rare traces of carbonate. The olivine yields also a group of brown and red products. Some of the chilled rocks at the margins may possibly have had a glassy matrix, but that is not likely in such large intrusives.

FIGURE 26. — Coarse mottling in Beaver Bay diabase, Highway No. 61, Sec. 33, T. 55 N., R. 8 W.

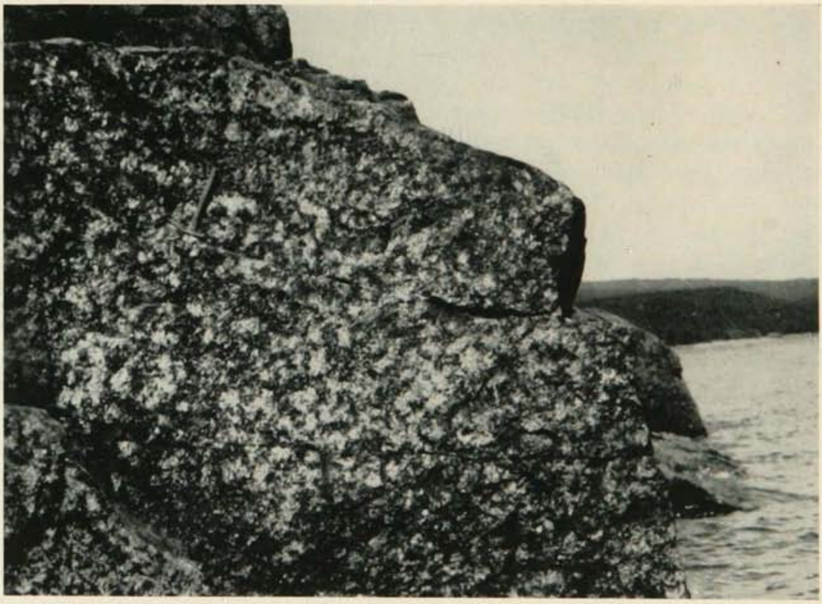


FIGURE 27. — Coarse mottling in Beaver Bay diabase, shore of Lake Superior, NE¼ Sec. 33, T. 55 N., R. 8 W.

The plagioclase is mostly labradorite with wide albite twinning bands and less commonly with Carlsbad twins; it has a vitreous luster and usually a light gray to green tint. Locally some is darker brown or even black from abundant inclusions. The composition was tested in thin sections by Winchell[14] and reported as mostly labradorite but close to bytownite in some sections. Recently the composition has been tested by the method of immersion in oils of different indices of refraction, which shows that the feldspars range from An_{45} to An_{76}, with most specimens near An_{60} (labradorite). The most sodic one is in the groundmass of a rock that is probably transitional to red granite. In such rocks the feldspar is zoned. The most calcic one is in a dark troctolite, almost a peridotite, in which early feldspar was probably concentrated by settling. In the porphyritic diabase the phenocrysts are a little more calcic than the groundmass plagioclase. Bytownite, which is present in several inclusions of anorthosite in diabase, is not really common in the diabase, but near the inclusions some xenocrysts from the anorthosite may be scattered in the diabase. This seems to be well illustrated by the brown feldspar in diabase below the brown anorthosite in the cliff about a mile northeast of Illgen City. The surface whitening of feldspar indicates alteration to kaolinite and sericite.

The pyroxene of the formation is largely augite, pale brown to pinkish brown in thin section. Many grains show the extra parting of diallage. Minute inclusions of almost opaque material, well oriented, have been described as schiller inclusions but cannot commonly be detected by the luster of the grains in the hand specimens. Augite when abundant may form euhedral or subhedral crystals, but in the diabases it fills in the spaces between plagioclase crystals. When the nature of the pyroxene was questioned, Winchell[15] reassured himself that it was not an orthorhombic mineral by both optical work and microchemical tests in which he found calcium. In the recent collections the several specimens showed pyroxenes of so many different appearances that tests were made of indices of refraction and extinction angles. Hypersthene was found in the dike east of Cramer. This weathers to a peculiar light gray, therein differing from common augite, which weathers black.

One occurrence of brown hornblende was discovered, but it may have been derived by the action of a later intrusive on a secondary green hornblende.

In most of northeastern Minnesota olivine is very rich in iron and weathers to a brown opaque aggregate that looks like limonite in hand specimens. These aggregates range widely in index, color, and birefringence, probably consisting of several minerals: bowlingite, iddingsite,

[14] *The Geology of Minnesota,* Vol. 5, describes about twenty-five specimens from this area.

[15] *Ibid.,* 5:200–05.

and hisingerite, with slightly different optical properties. Associated with the brown is a good deal of normal greenish and yellow serpentine and some colorless talc. The two latter products do not make use of the abundant iron of the olivine, so that much of the alteration product is mixed with magnetite and other iron oxides.

The alterations of the several ferromagnesian minerals do not invariably result in pseudomorphs of the originals, but the secondary products spread a little way, replacing the original minerals with radial or confused aggregates. At several places the secondary aggregates are so nearly spherical that careful work with thin sections was needed to prove that the rock was not an amygdaloidal lava flow. Some aggregates are clear examples of pseudo-amygdules. Magnetite and ilmenite as primary minerals are late to crystallize in much of the diabase, and fill interstices between plagioclase rods in exactly the same way as augite. In several of the rocks the iron mineral has formed a wormy intergrowth with silicates — biotite, augite, olivine, or feldspar. (See Figure 18.) In NE¼ NE¼ Sec. 28, T. 58 N., R. 6 W. the mottled diabase is coarse and contains an unusually large proportion of magnetite-ilmenite, in crystals up to an inch wide. Some form skeletal growths in the silicates, but the magnetite resists weathering and stands out in relief on the rock surface. These outcrops may be analogous to the large segregations of titaniferous magnetite in the gabbro some thirty miles northeast, but are much smaller.

Magnetite is usually filled with blades of ilmenite oriented along the octahedral planes. (See Figure 19.) It is doubtful if magnetite ever occurs in the diabases without this intergrown ilmenite. Natural weathering or hydrothermal attack has made visible a lattice pattern of leucoxene in some by altering the included ilmenite blades to leucoxene. Further alteration turns some of the magnetite to martite. Ilmenite also occurs as pure grains, ranging from irregular to elongate in shape in contrast to the more nearly equidimensional grains of magnetite. In several specimens the amount of ilmenite exceeds the amount of magnetite. Hematite, in addition to replacing magnetite, forms a network of veinlets in the more altered olivines. Polished surfaces also show a rather surprising number of tiny, scattered grains of sulphides, which are associated with magnetite and like it seem to be primary — chalcopyrite, bornite, covellite, and pyrite.

Weathering does not greatly change the appearance of the basic intrusives except as vegetation covers them. The feldspars are whitened by kaolinization and the olivine turns brown, but the net result is a whitening, so that at a distance facies which are high in feldspar somewhat resemble anorthosites. At places spheroids and brown soils occur.

The source of the basic intrusives is not definitely determined, but they lie scattered stratigraphically above the Duluth gabbro, resemble it in several details, and are almost connected with it in outcrops. It is not so likely that these upper intrusives derived their magma from the gabbro chamber (large as it is) as that they and the gabbro were both derived from a still deeper reservoir. The gabbro northeast of this area is cut by certain bodies of later diabase and of red granite and may have contributed fragments to form inclusions in the late rocks. It is certain, therefore, from the transgressing relations that not all the intrusives are of the same age. No doubt all are to be referred to Middle Keweenawan time, and some are so late in that period that they have inclusions of gabbro later than many of the flows. The prominent anorthosite inclusions must have been solid before the diabases were emplaced. It is probable that the Logan sills of extreme northeastern Minnesota and adjacent areas in Canada are of the same age as the Beaver Bay sills.

The diabases find little commercial use, but several facies have been used as building stone. A good quarry of very black rock has been opened along the highway about a mile southwest of Beaver Bay to furnish rock for bridge abutments and buildings at Gooseberry State Park. Dark granular rocks are now much prized for certain architectural purposes and a source so near water transportation might offer commercial possibilities.

Red Granite (Red Rock) and Rocks Intermediate between Red Granite and Diabase

Red granites are exposed at many places in the district mapped. Some are in large areas where their relations to other rocks are not clearly shown. Such an area occurs northeast and northwest of Finland. The more numerous exposures are those in which the red rock is part of a sill or dike composed chiefly of basic rocks. The red color appears largely in the upper parts of sill-like masses. Examples may be seen north of Finland and along the shore of Lake Superior in Sec. 28, T. 56 N., R. 7 W., west of the Palisades. Several contacts of red granite and diabase were studied in detail to ascertain whether there was a common sequence of one after the other, rather than simply a late facies of a magma cutting an early facies. At one place only did it seem that diabase intruded red granite with contact sharp enough to be covered by a finger (see Figure 28); but other contacts are gradational over wider contacts.

The red feldspar in these rocks seems to be a late product of a residual magma, more or less pegmatitic in its nature; like most pegmatites, the occurrences are commonly in segregated blotches, in indefinitely bounded dikes and stringers, and in upper zones. Possibly some of the red grains have been reddened by hydrothermal attack, which, however, changed their alkali content as well as their colors. Similar red granites are known throughout the area of such intrusive rocks in the Keweenawan region of Minnesota and have been studied in detail by several investigators.[16]

For the purposes of description, rocks in which all the feldspar is red

[16] W. S. Bayley, *The Eruptive and Sedimentary Rocks of Pigeon Point, Minnesota* (U. S. Geological Survey, Bulletin 109, 1893); R. A. Daly, "The Geology of Pigeon Point,

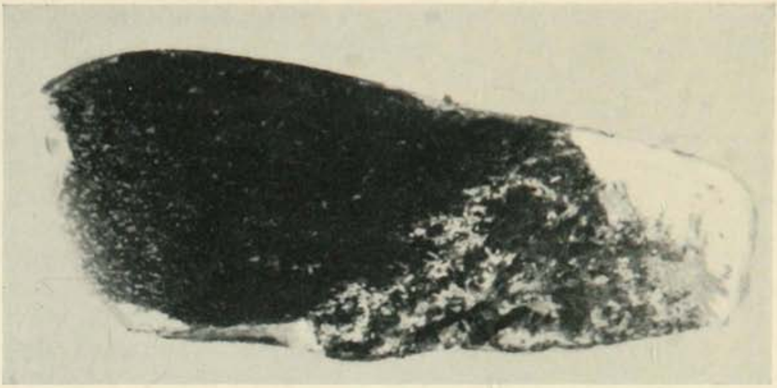


FIGURE 28. — Photograph of polished specimen, showing contact of diabase and red rock. ⅔ natural size.

are here termed red granite, and those which show some gray plagioclase with interstitial red grains, no matter how abundant, are classed as intermediate rock. Since many intermediate rocks seem to be related to large volumes of diabase and since they contain from 5 to 95 per cent red feldspar, it might be expected that the number of intermediate outcrops would be large as compared with the number at the red extreme; but it is probably very significant that there are many more outcrops of red than of intermediate rock. In other words, the separation of diabase and red granite is relatively sharp.

The red granitic rocks of the area are widely known as "red rocks," partly because of their rather characteristic bright brick-red color (though some may be bleached to pink or white), and partly because no other single name covers all the peculiar features shown by the rocks. Most of them are sodic granites with some graphic intergrowths of quartz and feldspar; granophyr might serve as their name. There are several, however, that have so little quartz as to be syenites; and several that have so much calcic feldspar as to be quartz-monzonites. The grain sizes range from coarse to fine granitoid, and the proportion of dark minerals from almost 0 to about 40 per cent. In this report "red granite" is used to include the several related facies of the red intrusives, members of the Beaver Bay complex.

Miarolitic cavities are very numerous in some of the outcrops and suggest the effects of mineralizers in the late stage of magma, or of very hot waters derived from the nearby magma. There is no ophitic or dia-

Minnesota," *American Journal of Science*, Fourth Series, 43:555–78 (1917); F. F. Grout and W. W. Longley, "Relations of Anorthosite to Granite," *Journal of Geology*, 53:133–41 (1935); F. F. Grout, "Anorthosite and Granite as Differentiates of a Diabase Sill on Pigeon Point, Minnesota," *Bulletin of the Geological Society of America*, 39:555–78 (1928); E. S. Bastin, "Hydrothermal Alteration in the Rocks of Pigeon Point, Minnesota," *Journal of Geology*, 46:1058–74 (1938).

basic pattern, or pseudomorph of such a pattern, so it is improbable that the red rocks were formed by replacement of diabase.

The essential minerals of the red granite are quartz, red feldspars, hornblende or light-colored augite, and locally biotite. Magnetite with some ilmenite is a very abundant accessory. Apatite is the chief of the transparent accessory minerals; others are titanite and zircon. Secondary minerals are kaolinite and hematite in the feldspars, hornblende, chlorite, epidote, carbonate, limonite, and leucoxene in the several dark minerals.

Quartz occurs in part of the red granite as grains of average granitoid size and relations, but in a much greater part of the rock is so minutely intergrown with feldspar that little quartz can be seen with the naked eye. In at least one rock of this area (Minnesota Geological Survey, No. M3173) there is evidence that quartz replaced some of the feldspar, for a large quartz grain outside the replaced feldspar has the same optical orientation as the small areas in the feldspar, which have a crude graphic pattern.

The feldspars of the red and intermediate rocks are very conspicuously dusted with kaolinite and hematite and are relatively difficult to identify by common optical methods. Some of the least dusty show (1) albite twinning, (2) gridiron twinning, (3) perthitic and antiperthitic intergrowth, and (4) chessboard twinning, in addition to the intergrowths with quartz. Tests with index oils on some of the least dusty materials show a range of plagioclase from andesine through oligoclase to albite. Nearly all grains, however, are conspicuously zoned, with the outer zones most dusty, with red, opaque dust. It is this outer red material that is most intergrown with quartz. If this is plagioclase, as suggested by its growth on a twinned plagioclase core, it is probably a potash-oligoclase and potash-albite or anorthoclase. Analyses of the rock indicate an abundance of both soda and potash, and are further evidence of the intermediate nature of the feldspar, for it is clear that if all the red feldspar were orthoclase or microcline, the potash would be more dominant, and if all were sodic plagioclase, the soda would be more dominant. Some of the early feldspars are euhedral, but most are corroded and very irregularly bounded by quartz and intergrowths. There are a variety of patterns in the thin sections, some with the regularity that makes them truly graphic, others grading into very irregular rounded and residual forms better described as poikilitic, especially where the quartz is more abundant than feldspar. There is no clear myrmekite or wormy pattern.

The ferromagnesian minerals of the red granite look peculiar to one familiar with more ordinary rocks. Commonly there are remarkably slender, large or small hornblende needles. In thin section these prove to be corroded and attacked, with rims of granular iron oxide and hydrothermal alteration to chlorite and carbonate. In some intermediate rock there is more augite than hornblende, and remnants of augite occur in hornblendes of a few granites. This augite is pale green and shows alteration to hornblende, which is commonly green, but in some exposures brown. The lighter-colored pyroxenes may be diopside, and in many of the rocks the pyroxene has the extra parting of a diallage. None of it shows evidence of late growth after the plagioclase, but it is commonly euhedral. Some of the intermediate rocks with small amounts of red feldspar have the red parts in the outer zones of, and filling interstices between, plagioclases that are euhedral as in diabase; in these the olivine is much altered and the labradorite partly albitized. The apatite needles of red granite and the red parts of intermediate rock are much larger and longer in proportion than the accessory apatite in most granites. Inclusions of mineral dusts are abundant in all the minerals, even in the quartz, but are perhaps least so in the early pyroxenes.

Several analyses of red granite and intermediate rock are available (Table 2, No. 5 and Table 1, Nos. 155 and 157). One analysis (Table 2, No. 6) with descriptions of two rocks, one diabase and the other red granite, has been reported, but the analysis is low in potash and is probably that of a diabase.

Reference should be made to a recent study of rock at Pigeon Point and a suggestion that much of it resulted from the hydrothermal replacement of diabase.[17] Several features of the rocks just described fit in with such a suggestion, but others do not. It was noted that no pseudomorph of diabase texture remains in the red granite, and that the pyroxene in some is euhedral. These facts make it seem likely that the red granite is a late magmatic rather than hydrothermal product, but the evidence is clear that great changes took place between early and late developments. Whether the late changes are deuteric or hydrothermal may be a matter of definition or a question of where to draw the line between two processes which grade into each other. Clearly the red granite is related to the basic rocks and developed from the sill magma as a late product.

The red granite and intermediate rock are locally used for building stone with satisfactory results. Several buildings have used all the varieties of stone from the different facies of the intrusives with pleasing effect.

Small Dikes and Veins in the Keweenawan

In nearly every outcrop of igneous rock in this area there are a number of small dikes or veins. No regularity in pattern or direction was detected, but some follow joints which curve and are offset in complex fashion. These have been studied in some detail by Roger W. Swanson,[18] who classified and described them petrographically as: (1) basalt and diabase dikes, (2) silicic dikes, (3) lamprophyres, (4) veins of quartz or hornblende or both, (5) clastic dikes (noted under Sediments; see page 31).

The large basalt and diabase dikes of the district send off apophyses and pinch out at the ends in minute stringers of trap. Only those less

[17] E. S. Bastin, "Hydrothermal Alteration in the Rocks of Pigeon Point, Minnesota," *Journal of Geology*, 46:1058–74 (1938).

[18] Master's thesis, University of Minnesota, 1937.

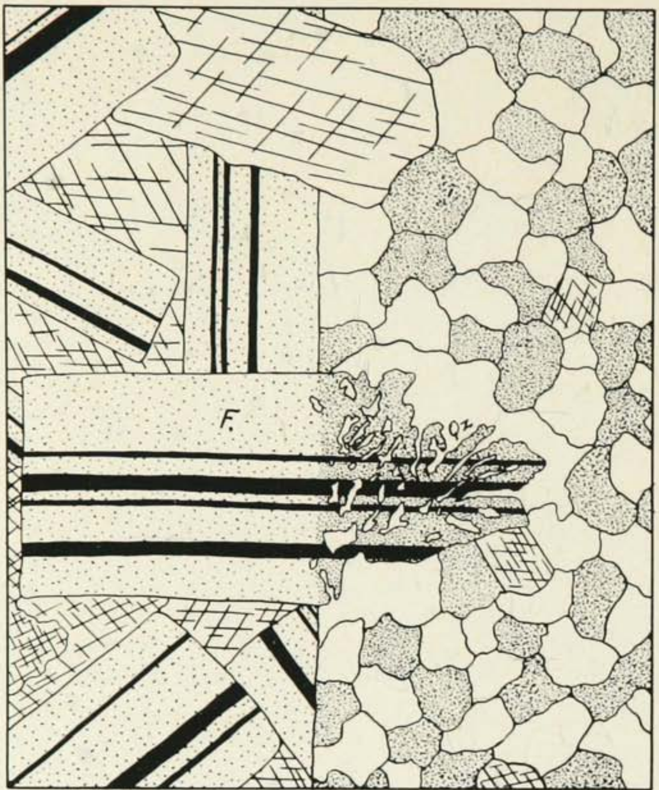


FIGURE 29. — Camera lucida drawing showing replacement of country rock feldspar (F) at contact of aplite dike. Quartz (Qz) in feldspar is optically oriented with adjacent grains.

than a few inches wide are here included as distinct from the larger basic intrusives. Small trap dikes cut nearly all the rocks so far described and seem to be manifestations of the latest igneous activity of the region, taking place after most of the rocks were cold. A few small pegmatitic diabase dikes, however, and possibly some other diabases, seem to be differentiates of the main intrusive now in their walls. They are not chilled. The anorthosite inclusions in large sills are also cut by small dikes, some of which are not chilled, so that there is evidence that the anorthosite was considerably heated. The dikes thus range from coarse to fine in texture; a few are porphyritic, and a few have had glassy groundmasses. The common minerals are like those of the basalt flows — augite, plagioclase, olivine, and magnetite — but there is less secondary hematite. The augite is altered in part to chlorite, and olivine is largely replaced by serpentine and iddingsite. Biotite and apatite are accessory; zeo-

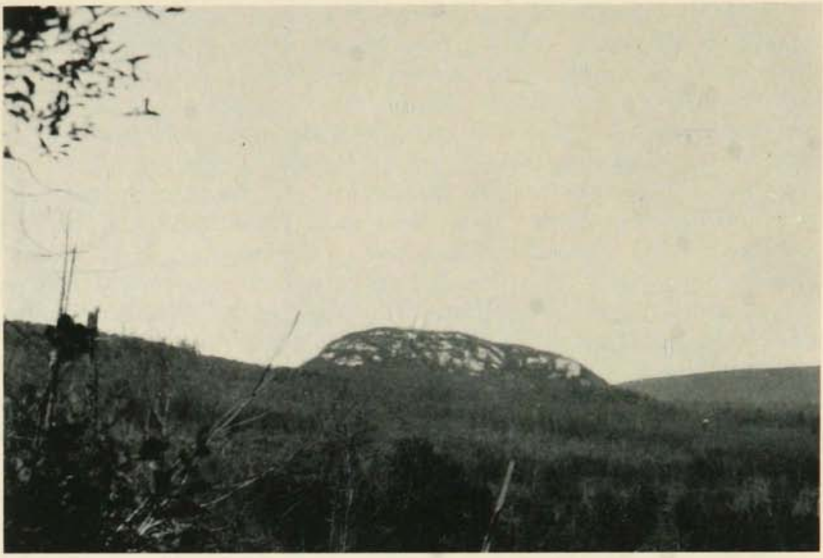


FIGURE 30. — Anorthosite monadnock, valley of Tettegouche Creek, Sec. 19, T. 56 N., R. 7 W.

lite is common in fracture fillings. A gradation toward silicic dikes may be indicated by scattered interstitial intergrowth of quartz and feldspar.

The small silicic dikes resemble red to white aplites, but one apparent aplite has a chilled rhyolite margin, as if the aplite magma had invaded a cold diabase not far from its source. These dikes are widely distributed. Some of the small ones fill groups of parallel joints. In one country rock mass they may be sharp-walled and straight, whereas in another they may be indefinitely bounded, irregular stringers. The essential minerals are quartz, a potash feldspar (either orthoclase or microcline or perthite), and albite or oligoclase. At the walls, especially where gradational, quartz is added to the country rock, replacing in an intergrowth some of the larger feldspars that may project into the dike. (See Figure 29.) Most of the feldspars are very dusty, more dusty than those in the wall rocks. There are some grains with intergrown quartz and some with chessboard twinning. The common dark minerals, hornblende, augite, and magnetite, make up less than 1 per cent of the light dikes. Apatite is accessory. In the centers of the dikes, apparently as late vug-fillings or replacements, are little masses of epidote, quartz, or hornblende, or mixtures of these. Several of the silicic dikes are confusedly mixed with somewhat darker rock, probably intermediate in composition, and the whole series seems probably related to the parallel series of coarser rocks in the large intrusives. They are at places cut by the later quartz veins mentioned below.

Lamprophyre dikes are sugary-textured augitites and limburgites, gray to black when fresh, weathering brown and rusty. The augitite is illustrated in the small, irregular dikes in an outcrop of diabase two miles northwest of Cramer. The walls are not sharp, but gradational, in spite of a pronounced change in texture. These dikes contain about 95 per cent pyroxene, part augite, and part bronzite. Plagioclase and magnetite are accessory, and limonite, carbonate, and chlorite secondary. Other such dikes carry a little biotite. The limburgites resemble the augitites, but have a small percentage of olivine. Both rocks have the same minerals as the diabase in the walls, and since the walls are not sharp R. G. Swanson (see note 18) suggests the possibiiity that they were squeezed out of the diabase magma about the time most of the early plagioclase had crystallized, leaving residual magma enriched in augite.

The numerous veinlets in the diabase are mostly of hornblende or quartz or both. Larger veins show amethystine quartz, and with the hornblende these suggest hydrothermal deposition. Only a few chalcedonic veins were seen, such as might result from cold or hot water at shallow depths. Along the hornblende seams the wall rock is uralitized and albitized for about half an inch.

Anorthosites

Distribution. — Anorthosite is very widely scattered in the area here mapped (Plates 1–5). Scattered areas are known outside (see pages 63–68), and large parts of the Duluth gabbro north of the area mapped are of the same composition. In the area near Lake Superior there are certain local concentrations near Split Rock lighthouse, at Beaver Bay and a few miles north, northeast of Lax Lake, at Nicado Lake, east of Finland and north of the road to Little Marais, and north of Cramer. There is a variety of sizes and shapes and compositions in each of these exposures, but in all there is a notable tendency for the larger bodies of anorthosite to resist erosion longer than the diabases and basalts, so that

Figure 31. — Typical anorthosite occurrence, Sec. 35, T. 57 N., R. 7 W. The covered areas may be partly diabase.

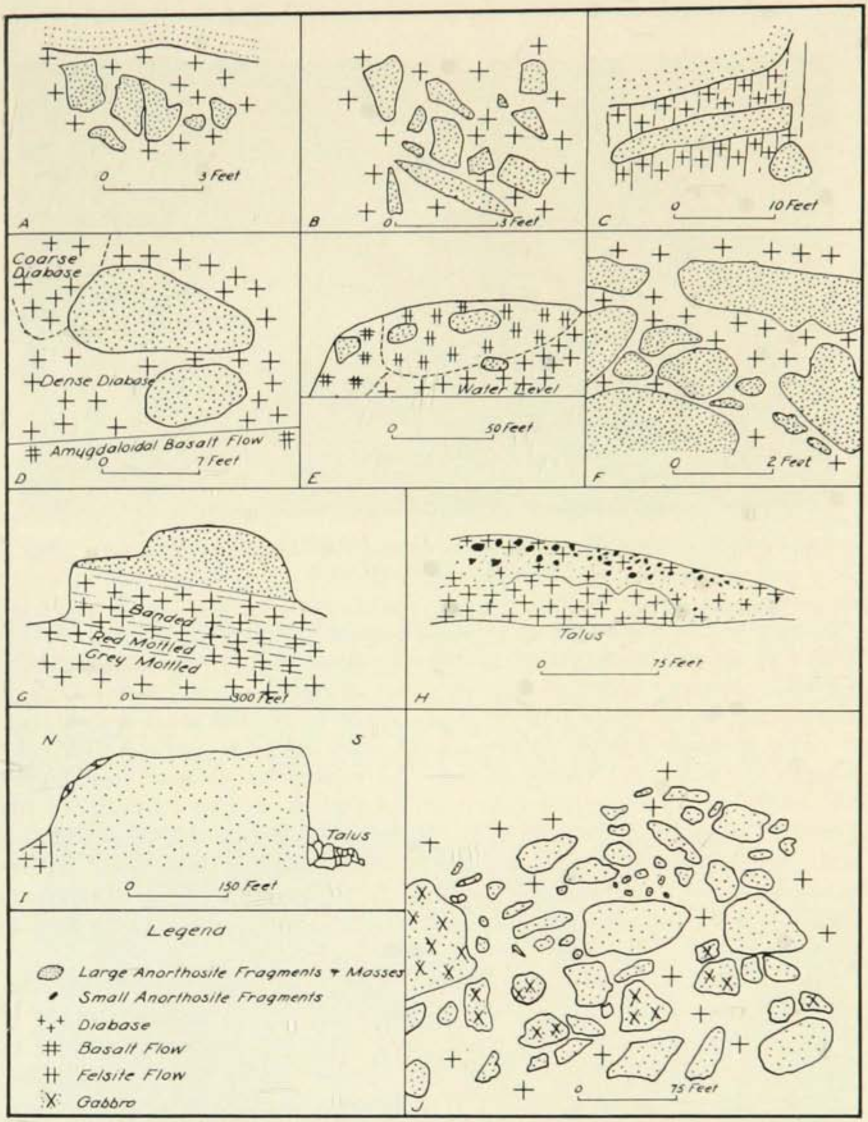


FIGURE 32. — Sketches of several anorthosite occurrences.

A. Anorthosite fragments in diabase which intrudes a large mass of anorthosite, SE¼ SW¼ Sec. 25, T. 56 N., R. 8 W.

B. Anorthosite fragments in diabase, SW¼ Sec. 6, T. 57 N., R. 6 W.

C. Anorthosite fragments in columnar diabase, bay east of Split Rock lighthouse.

D. Boulder-like masses of anorthosite in diabase, same location as C.

E. Anorthosite in diabase, basalt, and rhyolite, Beaver Bay.

F. Anorthosite in diabase, SW¼ Sec. 6, T. 56 N., R. 7 W.

G. Diagrammatic cross section of anorthosite hill, SE¼ SE¼ Sec. 34, T. 57 N., R. 7 W.

H. Diagrammatic cross section of anorthosite hill, SW¼ Sec. 6, T. 56 N., R. 7 W.

I. Diagrammatic cross section of anorthosite hill, NE¼ Sec. 3, T. 58 N., R. 6 W.

J. Anorthosite and gabbro inclusions in diabase boulder, SW¼ Sec. 21.

FIGURE 33. — Inclusions of anorthosite (white) in diabase, bay east of Split Rock lighthouse, Lake Superior.

white anorthosite knobs and peaks are conspicuous. (See Figures 30 and 31.) The several varieties of anorthosite described below are associated without apparent order, and no tendency was discovered for one kind of anorthosite to be characteristic of one sill or to be restricted to one area.

The geologic setting of the anorthosites is more uniform than the geographic position. Nearly all are surrounded by diabase (see Figure 32), only a few having been observed in basalt flows and a few in the red granite. None has been shown to be an independent intrusive, but for some the relation to other rocks is not clear, and in the absence of exposed contacts there may be doubt as to their origin. Of the thousands of masses studied not one shows any gradation from anorthosite to diabase.

The common relations to diabase are so widespread that illustrative exposures are too numerous to list. Rounded to angular blocks in medium-grained diabase are easily seen at Split Rock lighthouse, at Beaver Bay, at Silver Bay, at Beaver Island, and at many of the large inland occurrences. Some of the large masses extend down into the diabase with such steep sides that there may be doubt as to their being underlain by diabase. Accordingly, a few places may be mentioned where large masses clearly do have diabase below as well as around them. One is Carlton Peak, where a tunnel shows diabase beneath the main anorthosite mass. A very large mass south of Micmac Lake has red granite as well as diabase beneath.

In the diabase cliffs, most of which face northwest away from Lake Superior, several exposures, such as one northeast of Lax Lake (see Figure 32H), suggest that there is a tendency for the boulder-like masses of anorthosite to concentrate near the top. This impression is strongly reinforced by the fact that many of the high peaks are anorthosite, standing up above diabase slopes that look like the tops of sills only slightly eroded. If there is a real tendency, however, for the masses to rise in the diabase, it has not universally controlled the occurrences, for there are many large bodies of anorthosite near the bottom of diabase cliffs. There is a noteworthy exposure of such fragments near the base in the cliff east of Split Rock light. (See Figure 33.)

Some of the larger sills, such as the Beaver Bay diabase at Beaver Bay, have differentiated into light, mottled rock and darker rocks rich in augite and olivine. There is a distinctly greater proportion of anorthosite in the light than in the dark rock.

A few other occurrences of anorthosite in the area, outside of the medium-grained diabase, are noteworthy. The cliff just mentioned east of Split Rock light has some anorthosite masses so near the base of the intrusive that the diabase is chilled to a basalt. (See Figure 33.) On the north side of Highway No. 61 at East Beaver Bay is a similar exposure. (See Figure 34.) Some of the boulders along the central part of Beaver Bay may be in basalt flows, for the rocks in which they lie look like flows, but at some places the intrusives also develop an appearance like amygdaloidal basalt as a result of hydrothermal attack. At a rocky point on Lake Superior near Encampment Island (SW¼ Sec. 6, T. 53 N., R. 29 W.) there are anorthosite masses in a pseudo-amygdaloid. (See Figure 35.) Examples of anorthosite and gabbro fragments in true amygdaloid may be seen northeast of Silver Creek Cliff, southwest of the area here mapped.

FIGURE 34. — Inclusion of anorthosite in dense diabase, Highway No. 61, Beaver Bay.

At Beaver Bay the first outcrops east of the mouth of the river show anorthosite in red granite, but the exposures are somewhat confused and fractured. Part of the red formation may have been a surface rock rather than a differentiate of the diabase sill.

Size. — The largest bodies of anorthosite in diabase are over a quarter of a mile across, and the smallest are fragments of single plagioclase crystals so tiny as to be indistinguishable from the plagioclase of the surrounding diabase. Between these extremes are the great number of those mapped, a few yards across, and an infinite number of masses and fragments too small to show on a map. Commonly the small masses and crystal fragments are scattered near large masses as if derived from them. At a few places the breaking up of a large mass into smaller ones is perfectly clear. (See Figure 36.) The diabase dikes cutting into the large masses also seem to show that the blocks were cracked and in process of disruption while the diabase magma was still molten.

Shape. — The anorthosite masses almost invariably have boulder-like forms, some rounded and some angular. They may originally have

FIGURE 35. — Anorthosite inclusion in pseudo-amygdaloid, shore near Encampment Island.

been more angular than they now seem, because the rounded peaks of the larger outcrops have been eroded and exfoliation may have removed the sharper corners. Nevertheless, many cross sections in well-exposed cliffs show rounded masses, and it is likely that exfoliation, if not chemical attack, may have rounded inclusions before there was any exposure to weather. (See Figures 33 and 34.)

FIGURE 36. — Angular fragments of anorthosite in diabase, forming a breccia, SW¼ Sec. 6, T. 56 N., R. 7 W.

Color. — Most of the weathered anorthosite masses are slightly kaolinized white knobs, but the fresh surfaces show a vitreous luster and a variety of colors, pale green, pale gray, shades of brown, dark gray, and black. In some the mass as a whole is very light, but the dark minerals, chiefly olivine and its serpentinous alteration product, are concentrated in spots about an inch wide. More rarely there are dark bands. Most of the darker colors result from traces of dark minerals as inclusions in the plagioclase, not from the abundance of dark mineral. (See Figure 37; also Figures 21 and 22.)

Association. — The boulder-like masses of anorthosite are accompanied by inclusions of other rocks in the diabase intrusive. (See Figure 32J.) It is noteworthy, however, that in the whole district no exposure shows a dominance of any other rock over anorthosite in the inclusions, and many exposures show no inclusions except anorthosite. The other rocks are gabbros, with various proportions of dark minerals, and rhyolites and basalts, some of them amygdaloidal. In sizes and forms these show about the same range as the anorthosites. It is difficult, however, to be sure that any large mass of basalt flow is an inclusion, for the country rock around the diabase intrusive is basalt, more or less disturbed in position by the large intrusives. No such doubt arises as to the anorthosites, for none is known to outcrop as an independent intrusive for many miles in all directions.

Structure. — The anorthosites have a variety of internal structures. Several are banded with layers in which dark minerals are a little more abundant than in other layers. The attitudes of such layers are not con-

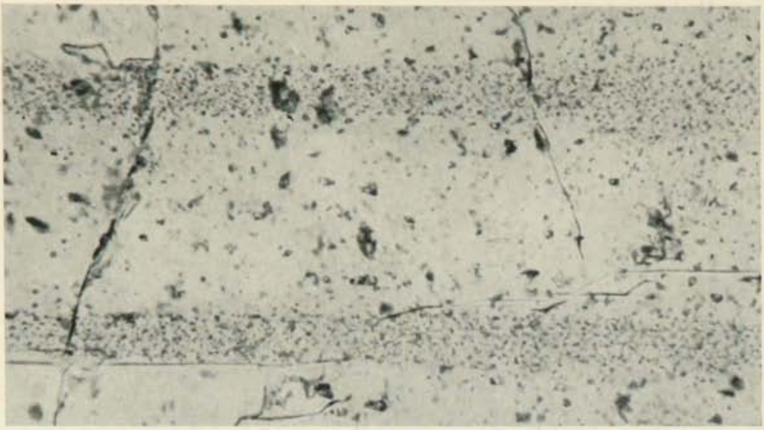


FIGURE 37. — Inclusions somewhat concentrated along zones in plagioclase of an anorthosite mass. x200.

stant even in adjacent masses. There is also very commonly a parallelism of platy feldspars in the anorthosite, but this is more pronounced in some than in others, and there is a lack of constancy of attitude.

Texture. — The anorthosites are not at all uniform in texture. They have already been generally described as constituting a sort of giant breccia in a diabase cement. (See Figures 32 and 36.) The masses themselves have a variety of textures, some of them brecciated with a cement of crushed or granulated feldspar. (See Figures 20 and 38.) Such masses can be seen north of Beaver Bay, where the road turns around a hill in Sec. 27, T. 56 N., R. 8 W.; and north of the road from Finland to Little Marais on the range line between R. 6 and 7 W., near the corner of Sections 7, 18, 12, and 13. Brecciation is more common near the borders than near the centers of masses. Those which have not been so obviously brecciated range from fine granitoid to remarkably coarse granitoid rocks. The largest measured cleavage face on a feldspar was one of 24 inches on a xenocryst in the diabase at Beaver Bay. Large masses not rarely have grains up to 5 inches in diameter, as was noted by Winchell.[19] Those with grains near 1/8 inch are common, but many have grains about 1/2 inch in diameter and are coarser than ordinary granitoid rocks. There is rarely any porphyry, but some of the brecciated and granulated rocks contain a mixture of coarse and fine plagioclase that bears some slight resemblance to a porphyry. The matrix of the breccias is so fine that it looks cherty in hand specimens.

Minerals. — The group of rocks included in diabase in this district is so dominantly anorthosite that there is little to suggest that the anorthosites were once part of a large formation of other rocks. Not 1 per cent of the masses are gabbros with less than 90 per cent feldspar. The average

[19] *The Geology of Minnesota*, 5:193.

of thirty-seven measured sections of anorthosite is between 97 and 98 per cent plagioclase. Many are more than 99 per cent plagioclase, and only a few as low as 90 to 95 per cent. The few gabbro inclusions associated with the anorthosite are rich in feldspar, not rich in ferromagnesian minerals.

With the feldspar are primary augite, olivine, magnetite, and rarely an orthorhombic pyroxene. Many thin sections do not show these dark minerals, but traces of augite and magnetite are visible in over half of those tested, and olivine in about one-fourth. Secondary minerals are not as constant as the primary ones. About a third of the thin sections tested had some chlorite; and about a third serpentine. A few rocks with granulated feldspar had zeolites. Other secondary minerals appearing in one to three of the thirty well-studied samples are: epidote, zoisite, magnetite, hematite, limonite, sericite, iddingsite, kaolinite, amphibole, biotite, leucoxene, and carbonate.

The alteration products are scattered through the plagioclase as well as around the grains. Stains of iron oxides and hydrous silicates permeate the feldspars in innumerable fractures and seem to have invaded some grains where no fracture is now visible. Certain zones or twinning bands have greater concentrations than others. (See Figure 37.)

The plagioclase of the anorthosites is dominantly labradorite, and the average of all is labradorite (An_{65}). The large number of samples tested, however, show a range from An_{57} to An_{85}, lapping over into andesine on one side and bytownite on the other. Careful optical work on four coarse-grained samples was done by Dr. R. C. Emmons of Wiscon-

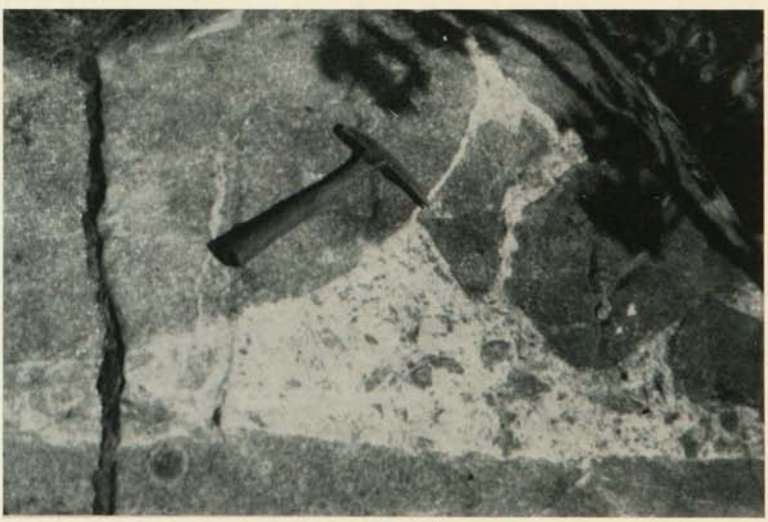


FIGURE 38. — Brecciated anorthosite, typical of many occurrences, Sec. 7, T. 56 N., R. 7 W.

TABLE 3. — OPTICAL DATA ON FOUR COARSE-GRAINED SAMPLES OF ANORTHOSITE
(Maximum Errors for Indices, .0005. R. C. Emmons, Analyst.)

	Near Split Rock	Silver Bay	Beaver Bay (Black Variety)	Lax Lake
α	1.5659	1.5638	1.5639	1.5665
β	1.5710	1.5680	1.5689	1.5723
γ	1.5761	1.5722	1.5734	1.5773
	.0102	.0084	.0095	.0108
2V observed	+88°	(86° ind.)	+88°	+88°
2V calculated	90°	90°	−87°	−86°

sin, whose results are given in Table 3. Chemical analyses (Table 4) calculated to norms indicate bytownite for nearly all samples, with the average near An_{71}.

One of the chemical analyses made many years ago, if calculated to feldspar molecules, indicates anorthite (An_{90}).[20] Though none of the other tests made over many years has confirmed this result, it seemed of sufficient importance to warrant a special visit to the locality, "a cove east of Split Rock," to see if anorthite could be found. Twenty of the masses in this exposure were sampled and tested by the method of immersion in index oils. Of these, thirteen are labradorite, four bytownite, and three are on the border line, labradorite-bytownite. None approaches anorthite very closely. It seems best then to consider anorthite a doubtful composition in this district until its presence can be confirmed by other samples. On the basis of these and many other tests, it seems that about 80 per cent of the masses are labradorite from An_{60} to An_{70}, and perhaps 15 per cent are bytownite from An_{70} to An_{75}. The brecciated anorthosite shows feldspar of about the same composition in the matrix and in coarser fragments. The specific gravities of the anorthosites range from 2.679 to 2.770, with an average of about 2.70; these figures agree fairly well with the optical determinations that labradorite about An_{65} is predominant.

The thin sections of anorthosite feldspars show wide twinning bands, with some crossed twinning. (See Figure 21.) There are many signs of deformation, especially in the brecciated samples. These are bent twinning, granulation (see Figure 20), slicing, faulting. The matrix of the breccia is so fine that twinning does not show in the fragments, and the proof that it is the same plagioclase as the original is found chiefly in the index of refraction. On the average the matrix has perhaps a little more of the dark minerals than the large fragments, and it is likely that some were introduced when granulation occurred. Even the coarse anorthosites have slightly more augite and olivine near the diabase contacts than elsewhere.

[20] A. C. Lawson, *The Anorthosytes of the Minnesota Coast of Lake Superior* (Geological and Natural History Survey of Minnesota, Bulletin 8, Part I, 1893).

TABLE 4. — ANALYSES OF ANORTHOSITES FROM THE MINNESOTA COAST OF LAKE SUPERIOR

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	49.78	47.40	51.45	47.25	47.97	51.54	50.68	51.45	50.59	49.14	53.01
Al_2O_3	29.37	29.74	31.94	31.56	32.45	28.87	30.67	28.47	29.88	32.72	30.04
Fe_2O_3	0.34		traces		0.62	1.06	0.21	0.80	0.35		
FeO	0.60	1.94		2.29		0.22	0.29	1.00	0.49		
MgO	1.07	0.57	0.27	0.27	0.16	0.39	0.42	1.07	1.18		
CaO	11.86	13.30	14.31	15.39	15.57	12.70	13.79	12.08	13.08	15.34	12.37
Na_2O	4.39	4.99	0.85	2.52	3.00	3.72	3.40	3.90	3.48	2.82	4.56
K_2O	0.46	1.56	0.21	0.37	0.53	0.27	0.09	0.33	0.12	0.03	
H_2O+ ...	1.76	1.64	0.68	0.40	0.38	0.82	0.50	0.63	0.79	0.21	
H_2O- ...						0.08	0.03	0.18	0.22		
TiO_2	0.00					0.12	0.07	0.15	0.05		
P_2O_5	traces					0.09	0.16	0.04	0.05		
CO_2						0.03	0.03				
MnO	0.08					0.01	0.01	0.02	0.01		
Total ..	99.80	101.14	99.71	100.05	100.68	99.92	100.35	100.12	100.25	100.26	99.98
Specific gravity	2.676	2.704	2.709	2.700		2.680	2.691	2.699	2.690	2.719	

1. Carlton Peak, Tofte, Cook County. *American Geologist*, 26:281 (1900), A. N. Winchell, analyst. Thin sections recently made show plagioclase (99 per cent), accessory and secondary iron oxides, and secondary zeolite.
2. Shore near Encampment Island, Lake County. Geological and Natural History Survey of Minnesota, Bulletin 8 (1893), p. 6. A more recent specimen taken at this place contains 92 per cent plagioclase, about 7 per cent zeolite formed from plagioclase, and small traces of augite and magnetite.
3. The constituent feldspar of anorthosite from a cove east of Split Rock Point, Sec. 5, T. 54 N., R. 8 W. *Ibid.*, J. A. Dodge, analyst. A specimen of feldspar taken recently is almost pure plagioclase, but several masses have as much as 2 per cent augite and some zeolite replacing the feldspar.
4. Boulder-like mass from the coast, two miles east of Beaver Bay. U. S. Geological Survey, Monograph 5 (1883), p. 438. A specimen taken recently is 98 per cent plagioclase with traces of augite, magnetite, and olivine, the last altering to serpentine.
5. Sec. 27, T. 56 N., R. 8 W., three miles northwest of Beaver Bay. *Economic Geology*, 22:26 (1927), R. J. Leonard and R. B. Ellestad, analysts. The rock is 99 per cent plagioclase with traces of augite and magnetite and secondary chlorite and zeolite.
6. Brown anorthosite on Highway No. 61, Sec. 1, T. 56 N., R. 7 W., R. B. Ellestad, analyst. The rock is 97 per cent plagioclase and 2 per cent reddish iron oxides, with traces of magnetite, augite, and secondary chlorite and sericite.
7. Split Rock quarry rock, Sec. 5, T. 54 N., R. 8 W., R. B. Ellestad, analyst. The rock has 95 per cent plagioclase, 2 per cent primary augite, and secondary zeolite and chlorite.
8. Black anorthosite, Beaver Bay, Sec. 12, T. 55 N., R. 8 W., T. Kameda, analyst. The rock has 98 per cent plagioclase, with traces of primary pyroxene and magnetite and secondary serpentine and zeolite.
9. Very coarse anorthosite with some dark grains, from a cove in Sec. 5, T. 56 N., R. 7 W., T. Kameda, analyst. The rock has 93 per cent plagioclase and 2 per cent zeolite, which probably formed from plagioclase; also about 4 per cent of secondary chlorite and serpentine after augite and olivine, of which only traces remain.
10. Bytownite, Crystal Bay quarry, Lake Superior. University of Toronto Studies, Geological Series, No. 35 (1933), p. 37, V. Ben Meen, analyst.
11. Calculated composition of labradorite, Ab_2An_3.

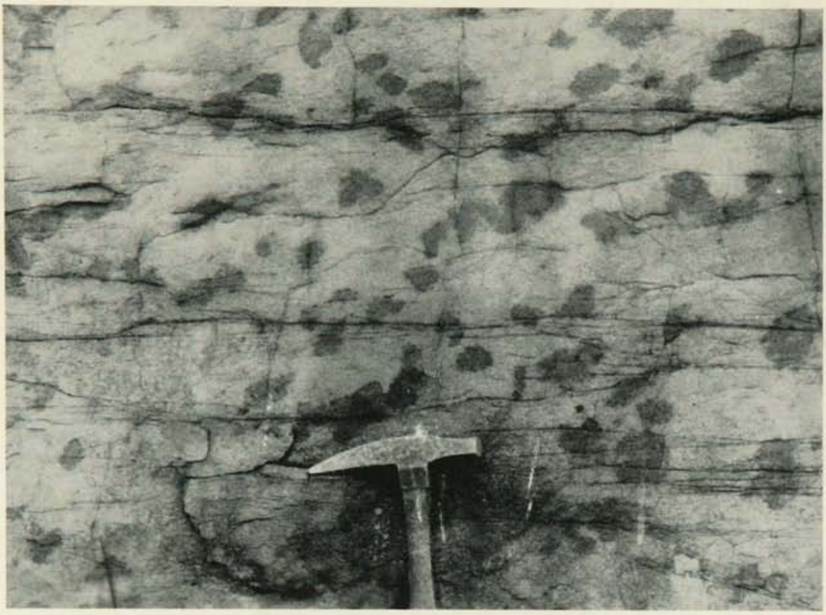


FIGURE 39. — Mottled or spotted anorthosite at Duluth. The dark areas are large olivine crystals poikilitically enclosing much plagioclase. Such rocks are abundant in the inclusions in diabase in Lake County.

The ferromagnesian minerals need little comment. Augite is late to crystallize in many of the anorthosites, and fills tiny chinks between the plagioclases. Olivine occurs commonly as areas perhaps half an inch in diameter, but so filled with plagioclase as poikilitic inclusions (see Figure 39) that the proportion of olivine in the rock is still very small. Magnetite occurs mostly in small, widely scattered grains, so that it is not easily removed. (See Figure 22.) The olivine is the first to be altered, probably by hydrothermal attack, and forms serpentine, which migrates a short distance into the feldspar as hazy green stains.

Chemical analyses both new and old are reported in Table 4. All the analyses of recent date and the best of the older analyses fall in the group called labradorose in the chemical system of classification. There is some uncertainty as to whether the iron oxides found by analysis are all in the ferromagnesian minerals seen in thin section — some may be isomorphous with alumina in the feldspar. All of the rocks analyzed, even No. 9, the darkest one, probably had over 95 per cent basic plagioclase in the original. These are anorthosites in all the systems of classification of rocks. There are other masses with 90 to 95 per cent of feldspar, here listed with anorthosite; and still others with 80 to 90 per cent of feldspar, here called highly feldspathic gabbro. Rocks with 80 to 95 per cent feldspar are termed anorthosite by some authorities, but not by others.[21]

Origin. — Most petrographers agree that anorthosite is a direct derivative of gabbro magma, but there is a good deal of disagreement as to the process involved. Bowen is a leading advocate of the idea that the anorthosite never existed as a magma, but resulted from the local accumulation of crystals in a magma that was liquid because it contained other constituents not present (or not in any such abundance) in the rock.[22] The objections to this idea come from field geologists, who have found at least some evidence that anorthosite magmas do exist and that they contain little other than the constituents of plagioclase. The theory is supported by the fact that some dikes injected into other rocks are solid anorthosite.[23] Bowen notes that such dikes are extremely rare.[24]

The argument is of less significance in this district than in some others, because the anorthosites seem to have been brought here in the solid state after having formed at other horizons. There are in northeastern Minnesota several other occurrences of anorthosite, some of which suggest an accumulation of crystals from a gabbro magma[25] and others a slight differentiation of a gabbro magma that was originally highly feldspathic. Winchell[26] noted that the masses near Lake Superior are "quite distinct from the ordinary condition of anorthosite in gabbro," where there are transitions and no sharp separations. He says those near Lake Superior have been considered: (a) intrusive into the diabase; (b) transported xenoliths; (c) indigenous to the diabase in which they lie; (d) the tops of Archean mountains around which the Keweenawan rocks flowed (Lawson's theory).

The origin of the anorthosites in this area is pretty well determined by the following facts: (1) They are fragments included in igneous rocks. (2) Fragments of other rocks are associated in several outcrops, but are not abundant. (3) Fragments of anorthosite lie chiefly in the large intrusive diabases, but rarely also in red granite and amygdaloidal basalts. (4) Fragments are in both sills, dikes, and flows. (5) Some are very large. These facts are discussed below.

1. The fragmental forms are recognized in the field. (See Figures 33–36.) It is only in the largest masses that there can be any question as to

[21] See A. Johannsen, *A Descriptive Petrography of the Igneous Rocks* (1937), 3:198.

[22] N. L. Bowen, *The Evolution of Igneous Rocks* (Princeton, 1928), pp. 170–72.

[23] A. L. du Toit, *The Geology of the Country Surrounding Nkandhla, Natal* (Geological Survey, Union of South Africa, Explanation of Sheet 109, 1931), Fig. 6, p. 63; W. J. Miller, "Adirondack Anorthosite," *Bulletin of the Geological Society of America*, 29:426 (1918); W. J. Miller, "Anorthosite in Los Angeles County, California," *Journal of Geology*, 39:338, 341 (1931); J. B. Mawdsley, *St. Urbain Area, Quebec* (Canadian Department of Mines, Geological Survey, Memoir 152, 1927), p. 19; C. F. Kolderup, "Anorthosites of Western Norway," *Report of the Sixteenth Session, International Geological Congress* (1936), 1:290.

[24] N. L. Bowen, *op. cit.*, p. 170.

[25] Grout and Schwartz, *op. cit.*, pp. 48–52.

[26] *The Geology of Minnesota*, 5:65.

their lying in a matrix such that a magma of different composition brought them to their present surroundings. At Beaver Bay and Carlton Peak Dr. Lawson [27] thought the larger anorthosite outcrops were only the tops of masses that extended downward to great depths as mountains. The evidences of regional structure are against this,[28] for the flows dip gently under the sills of diabase in which the anorthosites now lie. At Carlton Peak a tunnel was run 75 feet into the base of the bluff by the owners, the Minnesota Mining and Manufacturing Company of St. Paul. Dark diabase was found below as well as around the anorthosite, thus indicating that even some of the largest masses are undoubtedly fragments, and all of them may be. In the common host rock, diabase, there is another line of evidence that the anorthosites were solid and cold before the diabase magma carried them to their places: namely, the anorthosites are coarse-grained and in some occurrences suspended in chilled diabase. A good example occurs along the bluff east of Split Rock light. (See Figure 33.) The common brecciation of anorthosite may be further evidence that cold blocks were suspended in hot magma.

The notably rounded forms of many of the anorthosite inclusions are to be explained by friction in transportation,[29] and perhaps by spalling at the corners when cold rock was immersed in hot magma. The rounded forms have been noted as criteria of indigenous origin, that is, of segregation in the diabase, by a process of drawing together like that producing glomeroporphyry, continued until the aggregate was large. This was mentioned in the description of the anorthosite in the Logan sills of Cook County,[30] but the accumulations found there are very different from these.

2. No one questions the fragmental origin of the few scattered inclusions of gabbro, basalt, and rhyolite in the diabase. They have undoubtedly been picked up by the diabase magma on its intrusion from deep sources to its present surroundings. The anorthosite fragments have the same relation to diabase as the recognized gabbro fragments, except that some anorthosite fragments are exceptionally large. All who have made a careful study of the anorthosites have recognized this similarity in the occurrence and relations of inclusions of other rocks to the inclusions of anorthosite.

3. The occurrence in a variety of igneous rocks, intrusive and extrusive, implies a deep source for the anorthosite fragments, perhaps in the walls of the deeper reservoirs that supplied the flows and intrusives, or more probably between those reservoirs and the surface. The several

[27] A. C. Lawson, *op. cit.*

[28] As was reported by A. H. Elftman in an account of field work during 1893. *The Anorthosytes of the Minnesota Shore of Lake Superior* (Twenty-second Annual Report of the Minnesota Geological and Natural History Survey of Minnesota, 1894), pp. 174–80.

[29] Sidney Powers, "The Origin of Inclusions in Dikes," *Journal of Geology,* 23: 181 (1915).

[30] Grout and Schwartz, *op. cit.,* p. 42.

kinds of magma may have come from different reservoirs or parts of reservoirs, but to reach the surface or sill chamber they had to inject the rocks along the route. The variety of host rocks[31] is clear evidence that the labradorite did not accumulate in place from the surrounding magma; such uniform feldspar would not result from magmas as different as rhyolite and diabase.

4. The occurrence of fragments in flows, dikes, and sills clearly proves that the wall rocks of the present masses could not have contributed the fragments. They were picked up during their rise from the depths.

TABLE 5. — SPECIFIC GRAVITY OF ANORTHOSITE AND DIABASE MAGMA

	Anorthosites of Area Mapped	Minnesota Diabases
Old Estimates	2.676	2.89
	2.703	2.91
	2.704	2.99
	2.700	2.97
Rough tests on hand specimens	2.707	
	2.71	3.01
	2.76	2.93
	2.69	3.15
	2.77	2.88
	2.73	2.95
	2.76	3.04
Careful recent tests	2.7084	2.8908
	2.6903	2.9337
	2.6993	
	2.6799	
	2.6913	

5. The anorthosite masses range up to nearly half a mile in length. Many are several hundred yards long. The main objection to the idea that such anorthosites are fragments brought up by intrusive magma is their occasional enormous size. Nevertheless, the diabase dikes which form the matrix for some fragments, and which probably fed the sills, are large enough to permit the rise of a magma holding such fragments. The dike east of Cramer and one three miles west of Beaver Bay are examples of large intrusives through which such masses could be carried.

One of the problems involved in the theory that fragments were carried up from the depths by diabase is the specific gravity of the anorthosite and of the diabase magma. Of course, the magma has long since cooled, so that its specific gravity must be estimated from that of the cold rock, by calculating the probable differences resulting from heating and melting. The available data are given in Table 5. These figures are

[31] These were observed in the early work of the survey. Grant reported olivine gabbro, *The Geology of Minnesota*, 5:557; Elftman noted amygdaloidal basalt, *ibid.*, 5:404, footnote.

not very different from those used by other investigators of the relative densities of rocks, crystals, and magmas.[32]

Careful work indicates that the rough tests gave slightly higher (.02 to .08) results than the correct ones, but the differences between anorthosite and diabase are of the same order of magnitude. If estimates of specific gravity at different temperatures are based on the averages of careful tests, they may start with 2.694 for anorthosite and with 2.912 for diabase:

	Crystalline at 20°	*Crystalline at 1100°*	*Liquid at 1100°*
Anorthosite	2.694	2.627	
Diabase	2.912	2.839	2.633

It seems likely that the anorthosite, if included without being much heated, would be heavier than the liquid diabase magma; but if immersed for a long time, or immersed in the depths where all rocks are hot, it might be lighter than the diabase magma. Many masses are near the top and some near the bottom of diabase sills, as accords with the specific gravity data. (See Figure 40.)

The suggestion of origin by transportation of fragments from below is not a new one in connection with Minnesota rocks. Such an origin, however, has been so rarely mentioned in the explanation of occurrences in other parts of the world that the theory was critically restudied. It was found that no other explanation could account for the facts. Winchell[33] repeatedly referred to "transported blocks," "foreign masses" of anorthosite, and diabase surrounding "isolated masses" of anorthosite. Elftman writes of a "mass transported" by the diabase.[34]

If it is granted that the anorthosite masses are fragments picked up by magmas moving from some deeper reservoir toward their present location, an examination of the older rocks of the region is in order to determine whether those exposed would have been able to furnish large blocks of anorthosite. Within a few miles north of the area mapped is the enormous Duluth gabbro, with structures indicating that it dips under the rocks of the Lake Superior shore. Below that is a complex of older rocks of considerable variety. The nearest known anorthosite in the older rocks is far away at Rainy Lake; and at that place the rocks are so much altered hydrothermally that it appears unlikely they could supply anorthosites as fresh as those in this county. (See Table 6.) The Duluth gabbro, then, seems to be the only exposed formation that needs consideration.

Winchell assumed that the gabbro was the source of the fragments,[35] and that their rounded forms resulted from collision of the fragments with

[32] See R. A. Daly, *Igneous Rocks and the Depths of the Earth* (1933), pp. 276–77; and L. L. Fermor, "On the Basaltic Lavas of Bousawal," *Records of the Geological Survey of India*, 58:196–238 (1926).

[33] *The Geology of Minnesota*, 4:299; 5:181–82.

[34] *Ibid.*, 4:301.

[35] *Ibid.*, 5:66–67.

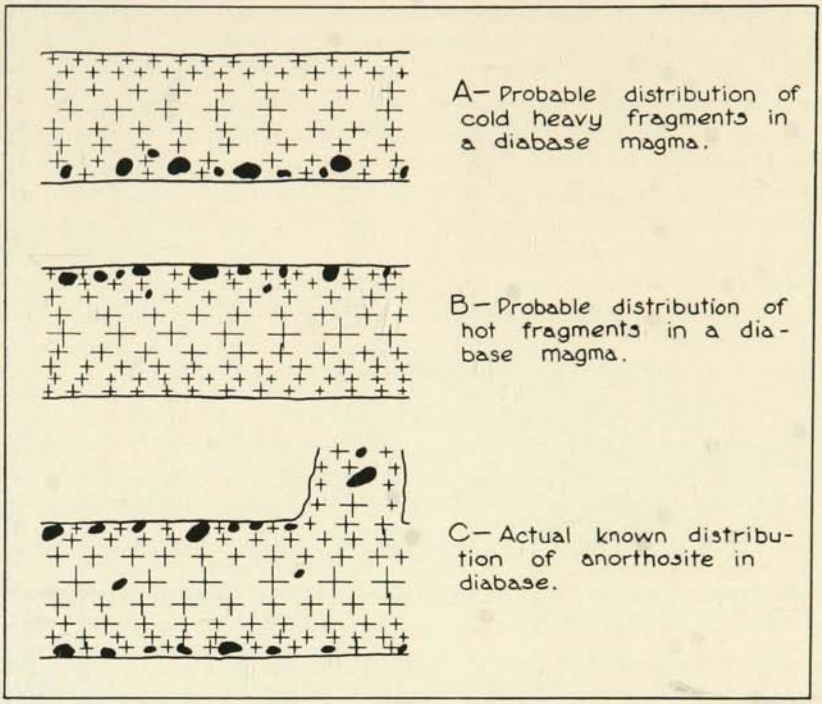


FIGURE 40. — Relations of anorthosite to sills and dikes.

each other during transportation by the diabase magma. He refers to the fact that in T. 61 and 62 N., R. 10 and 11 W., there are many large outcrops of anorthosite that stand up topographically and are as fresh and coarse as those near Lake Superior.[36] A more extensive survey of the gabbro has been in progress in the years since Winchell wrote; in view of the results, it still seems probable that the gabbro supplied the fragments. The Duluth gabbro formation has several outcrops of anorthosites at Duluth. Some have coarse grains, up to one inch, some fine and gray, some spotted with large poikilitic olivines like those at the old Crystal Bay quarry and elsewhere. (See Figure 39.)

Northeast of Duluth, wherever exposures of the gabbro are abundant, a traverse across the formation reveals abundant anorthosite in large areas. It is noteworthy that these occur chiefly as zones or bands alternating with darker gabbro bands. Little if any of the Duluth gabbro area has boulder-like masses of anorthosite in darker gabbro, but the intrusive is so large that part of it may have been intruded early enough to supply fragments to later facies. Examples of anorthosite inclusions are known even in the city of Duluth. Great areas of anorthosite bands may be seen

[36] *Ibid.*, 4:301.

TABLE 6. — OTHER ANORTHOSITES OF MINNESOTA THAT MIGHT HAVE SUPPLIED FRAGMENTS TO THE LAKE COUNTY AREA

	1	2	3	4	5
SiO_2	52.30	49.39	45.58	47.94	46.24
Al_2O_3	28.79	29.08	27.70	25.84	29.85
Fe_2O_3	.49	.34	1.03	1.92	1.30
FeO	.72	2.89	2.43	1.03	2.12
MgO	1.06	2.26	2.75	1.34	2.41
CaO	11.93	13.06	15.50	18.72	16.24
Na_2O	3.99	2.89	1.64	.68	1.98
K_2O	.30	.10	.11	.05	.18
H_2O+	.39	.34	2.20	1.77	
H_2O-	.05	.09	.10	.03	
TiO_2	.18	traces	1.00	.34	1.03
S		none		traces	
MnO	.02	.04	.05	.05	traces
Total	100.41	100.57	100.32	99.89	101.35
Specific gravity	2.77				2.85

1. Sample from along Highway No. 1 north of the area mapped, Sec. 32, T. 61 N., R. 10 W.
2. Duluth gabbro from north of Proctor.
3 and 4. Two samples from an island in Rainy Lake close to the Ontario boundary. Much altered to zoisite.
5. Same formation as 3 and 4, from the mouth of the Seine River, Ontario. *Journal of Geology,* 4: 909, William Lawson, analyst.

along the Kawishiwi River, at Little Saganaga Lake, and even along Highway No. 1 between Ely and Finland. Some of these seem to be continuous anorthosite for miles, and exhibit variety in both color and texture. Taken together, their character and position is such as to make the Duluth gabbro formation seem a likely source of supply for the anorthosite masses. (See Table 6.) Whether the diabase and other magmas that contain the fragments came from the Duluth gabbro chamber or from some deeper chamber that supplied both intrusives is uncertain.

There remain, however, three puzzling features, not thoroughly explained by this outline of origin. First, a surprising number of the anorthosite masses near Lake Superior are coarser-grained than any mass so far reported in the Duluth gabbro formation. This difference is not just a slight one, but a marked contrast. The largest grains in the gabbro are about one inch long, but some of the boulder-like inclusions have grains many inches long. These are difficult to explain as derived from the gabbro, but one may speculate that some coarser facies of the gabbro exist at depth; or that long immersion in the diabase magma caused a recrystallization of some masses. Notably coarse grain is characteristic of anorthosites the world over, but this does not constitute proof that the Duluth gabbro had coarser grains than have been observed. In the second place, a large part of the boulder-like anorthosite near Lake Superior is a light-colored, transparent feldspar rock, whereas the anorthosite bands of the gabbro are mostly a medium gray. This superficial difference in appearance is enough to raise doubt as to their common origin. Finally, it may be remarked again that if the gabbro was the source of the anorthosite fragments, we should expect to find several times as many gabbro as anorthosite fragments, because the anorthosite makes up only a small part of the total gabbro formation. An explanation may be found in a suggestion advanced by Powers[37] after a study of a dike with inclusions. The dike probably crossed several formations, but has millions of anorthosite fragments and few others. He says the explanation must lie in an unusual amount of shattering of that very compact rock, anorthosite.

These facts leave some doubt whether the anorthosites are derived from known formations; but among the known formations, the Duluth gabbro is the only one likely to have supplied the fragments.

Anorthosites of Adjacent Areas

The area mapped in detail for this report contains most of the occurrences of these peculiar anorthosite masses, but it has been known from the earliest explorations that there are outlying masses. Of these, Carlton Peak near Tofte in Cook County, about ten miles east of the area mapped, is the most conspicuous. Early reports also refer to small occurrences on the shore east of Encampment Island. These occurrences have been re-examined and are described below. During field work carried on by the geologists of the Minnesota Geological Survey, other xenoliths have been discovered in the diabase intrusives of the north shore of Lake Superior, until now occurrences are known as far southwest as Duluth and as far northeast as Wauswaugoning Bay. Reconnaissance shows similar masses in diabase far north of Carlton Peak, and it is very probable that as detailed mapping is done in the region not as yet so mapped, others will be found.

Duluth.—Within the city limits of Duluth, in SW¼ NW¼ Sec. 6, T. 50 N., R. 13 W., there is a boulder-like inclusion of pure anorthosite in coarse, somewhat porphyritic and feldspathic diabase. The inclusion is about 8 by 12 feet on the exposed surface and has a sharp contact with the diabase, which is not chilled at the contact, indicating that the inclusion was thoroughly heated. The feldspar of the inclusion is labradorite. The diabase is part of what has been called the Northland sill complex, which may be an offshoot of the Duluth gabbro. The occurrence is in all respects similar to many occurrences of anorthosites here described. Several anorthosite masses of similar form occur in red rock differentiates of the intrusives at Duluth.

Stony Point.—Stony Point is a rocky, rounded projection in Lake Superior two miles southwest of Knife River. On the west side of the point at the lowest exposures of the Stony Point sill are inclusions of anorthosite in diabase. This is in SE¼ Sec. 2, T. 51 N., R. 12 W. At the time the examination was made (1938) only two masses could be studied, as the others lay below water level. The larger is about 12 by 12 feet in

[37] Sidney Powers, *op. cit.*, 23:174–77.

horizontal dimensions and the smaller about 4 by 4 feet. These inclusions have the typical rounded form, and anyone who saw them after examining the anorthosites of Lake County would have little doubt that the inclusions of the two places have a similar origin.

Two Harbors. — A mass of anorthosite lies in the southern part of Sec. 1, T. 53 N., R. 11 W., five miles due north of Two Harbors. The mass is similar to those elsewhere in Lake County, but is in an area of thick brush with few rock exposures. The exposures are low, rounded masses, and the anorthosite can be seen for about seventy-five feet east and west, though only a few feet north and south and vertically. Much of the rock which is exposed nearby is hornfels, but diabase occurs at the east end of the anorthosite exposure. A road-cut in black diabase occurs on the highway near the southeast corner of Section 1.

About two and one-half miles northeast of this occurrence and approximately 600 paces south of the northeast corner of Sec. 5, T. 53 N., R. 10 W. is another occurrence of anorthosite. This is on a bare rock bluff, which faces south and extends east and west for fully 1,000 feet. The major portion of the bluff consists of coarse red granite, but to the west it grades suddenly to diabase. In the diabase are masses of anorthosite, the largest perhaps 60 feet across. About 200 paces farther west is a ravine with many diabase exposures, but no more anorthosite was observed.

Encampment Island. — Encampment Island is about five miles northeast of Two Harbors and has been a landmark since early explorations. The anorthosite masses are actually in a cove in SW¼ Sec. 6, T. 53 N., R. 9 W., about one mile northeast of the island and about 1,000 feet east of the Crow Creek bridge on State Highway No. 61. Lawson[38] described the occurrence in detail but there is uncertainty whether the matrix of the anorthosite is an amygdaloidal flow or a pseudo-amygdaloidal sill. The boulders range from 2 inches to 20 feet across. (See Figure 35.) Truly amygdaloidal rocks, probably in both sills and flows, carry anorthosite and other fragments from Encampment beach southwest almost to Silver Creek Cliff; also farther southwest, halfway from Silver Creek to Stewart River.

Carlton Peak. — Carlton Peak is one of the landmarks (see Figure 41) of the north shore of Lake Superior and has been described by Norwood,[39] Irving,[40] and Lawson.[41] It lies in Sec. 20, T. 59 N., R. 4 W., about ten miles slightly north of east of the large anorthosite masses in Lake County. (See Figure 42.) The intervening area is mainly low, and outcrops are not numerous.

[38] A. C. Lawson, *op. cit.*, p. 10.

[39] J. G. Norwood, in D. D. Owen, *Report of a Geological Survey of Wisconsin, Iowa, and Minnesota* (1852), p. 380.

[40] R. D. Irving, *The Copper-bearing Rocks of Lake Superior* (U. S. Geological Survey, Monograph 5, 1883), pp. 55, 329.

[41] A. C. Lawson, *op. cit.*

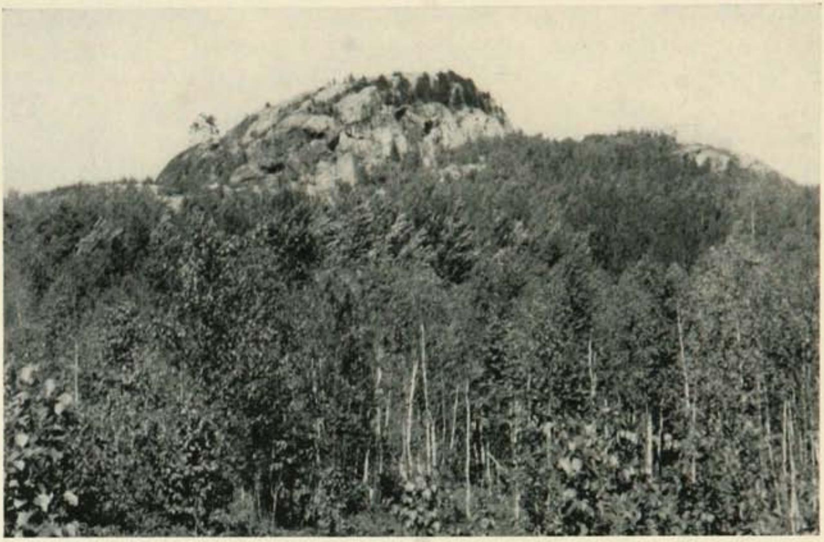


FIGURE 41. — Isolated anorthosite hill, Carlton Peak, Tofte.

The peak is a huge, rounded mass of anorthosite and diabase, which rises 927 feet above the level of Lake Superior (602), although its base is only a little over a mile from the shore. The Sawbill Lake road runs close to the peak on the east side, and a trail runs along the north side and gradually ascends the peak on the northwest. Some of the exposures are shown in Figure 41. The anorthosite and diabase are much more widely distributed than is indicated by the peak proper. Some outlying masses occur a short distance north of the peak, others to the south.

The peak consists of two very large masses of anorthosite and several subordinate masses. Some of these are clearly separated by diabase. The largest mass is composed of a pinkish, somewhat impure feldspar with spots high in ferromagnesian minerals. This rock weathers more readily than most of the masses of Lake County. The associated diabase is medium-grained and much less resistant than the anorthosite; it occupies the saddles between the anorthosite humps. Patches of zeolite an inch or more across occur locally in the anorthosite.

On the southwest side of the main mass of anorthosite, at the foot of a high cliff, a prospect tunnel has been driven beneath the hill N. 80° E. The size of the dump indicates a tunnel fully 100 feet long, and the excavated material is all very dark, coarse basic diabase. This seems to prove that the anorthosite is underlain by diabase.

Lawson believed Carlton Peak to be a mass of Archean anorthosite projecting through the Keweenawan lavas, but the tremendous thickness and regional dip of the north-shore flows were not known at that

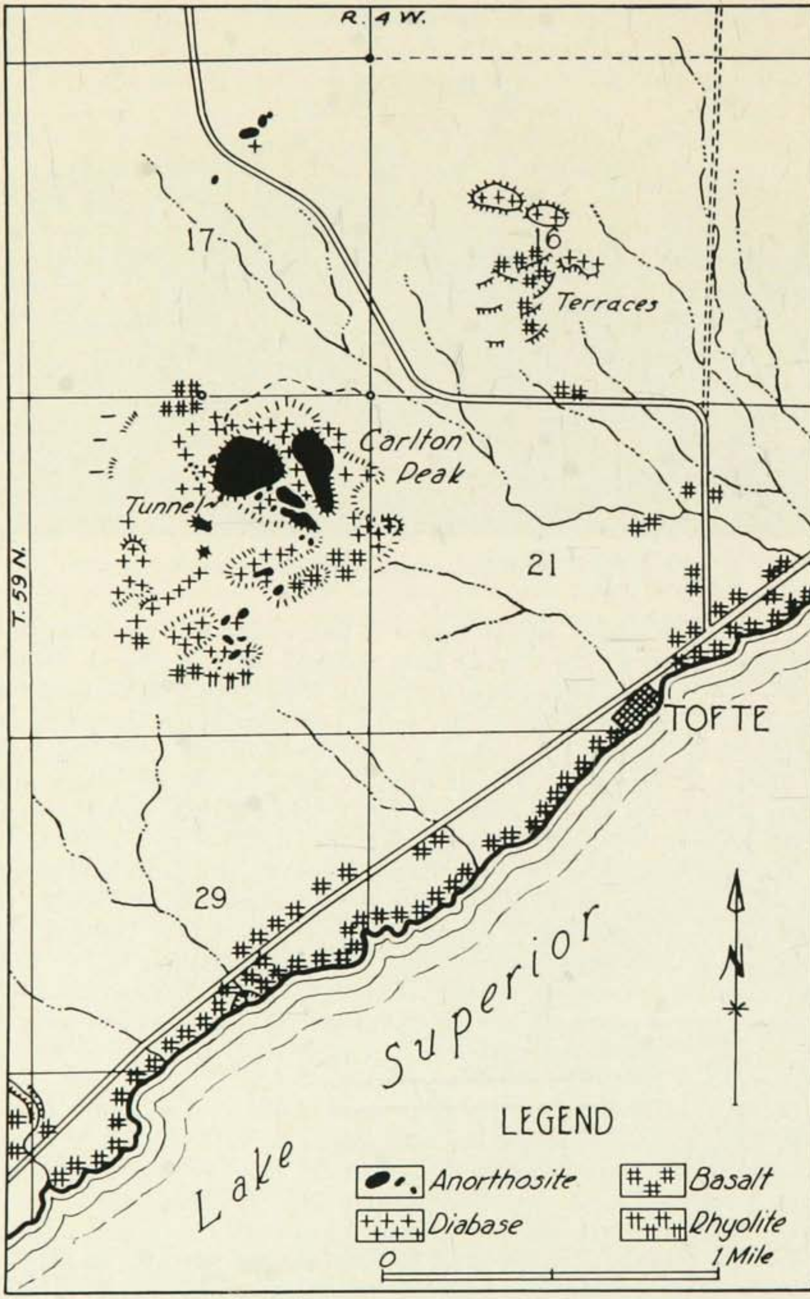


FIGURE 42. — Sketch map of Carlton Peak and surrounding area.

time, and the intrusive diabase with which the anorthosite occurs was not recognized. The tunnel referred to above shows that the intrusive diabase probably underlies the anorthosite mass. There are probably much better exposures around the peak now than formerly, since forest fires have burned off the moss. Early descriptions do not mention the diabase, which may now be seen at several places. The belt of diabase may be traced some distance to the northeast. To the southwest it seems to end northeast of Cross River, as no diabase is exposed along the river or lake shore.

The outlying anorthosite xenoliths, like the main mass of Carlton Peak, contain olivine spots and are brownish or wine-colored. South of these exposures are both felsite and basalt flows. Basalt also is exposed northwest of the main mass. The entire exposure of diabase and anorthosite seems to be an erosional outlier of a diabase sill. North of the peak, in the northeast quarter of Section 17, are three small masses of anorthosite with a small exposure of diabase. One outlier, 30 paces across, is exposed about two miles northeast in some weathered diabase, in the eastern part of Sec. 15, T. 59 N., R. 4 W.

Grand Marais. — About two miles east of Grand Marais on the shore of Lake Superior, in SE¼ Sec. 14, T. 51 N., R. 1 E., is a diabase dike about 10 feet wide which contains both red granite and anorthosite inclusions. The dike strikes N. 15° W. and dips 65° E. There are exposed about forty fragments of anorthosite, ranging from 1 to 8 inches across.

Cherokee Lake. — Donald Taylor, mapping in the area of the Duluth gabbro and red granite, found two intrusives about 100 yards across, full of inclusions, some of which are anorthosite. These are in Sec. 1, T. 63 N., R. 4 W., about twenty-five miles north of Carlton Peak. The one is about at the northeast corner of the section north of the portage from Cherokee Lake to Fay Lake. The second is on a hill nearer the east quarter corner. In both there are fragments of anorthosite up to 25 feet or more across; and a variety of textures and gradations to other rocks in the fragments.

Mesaba Lake. — On the shores of Duck Lake and Mesaba Lake in T. 63 N., R. 5 W. there is a complex of rocks forming a belt southwest across the gabbro area. There are anorthosite inclusions in granites, in diorites, and in diabase. On Duck Lake the anorthosites are so large that it would require careful mapping to be sure that all were included in diabase, but the smaller ones there and on Mesaba Lake in the eastern part of Section 3 are surrounded by diabase in much the same way as are those at Beaver Bay. On Dent Lake in the north part of Sec. 8, T. 63 N., R. 5 W. anorthosite fragments lie in an intrusive that looks like granodiorite rather than diabase. The estimated proportions of anorthosite are different at different points: 10 per cent of the outcrops on Mesaba Lake and southwest; 20–30 per cent on Hub Lake; 40 per cent on the north side of Duck Lake; 70 per cent on the south side of Duck Lake. The rocks in this belt look somewhat more altered than those on the shore of Lake Superior, possibly because there is a large gabbro mass on each side. On the north side, at Hub Lake, the main gabbro is rich in feldspar.

Rove Slate Area.—In mapping the Logan sills of the Rove slate area in the extreme northeastern corner of Minnesota, the writers noted several occurrences of anorthosite.[42] Some of these, such as the occurrence in the Pigeon Point sill, seem to have formed by rising and clustering of plagioclase crystals.[43] Others, however, are rounded xenoliths resembling those of the main area of anorthosites described in this report—probably foreign inclusions in the diabase.

On the shore of Moss Lake in T. 65 N., R. 1 W. are rounded masses of anorthosite and anorthositic diabase embedded in porphyritic diabase and ranging from a few inches to several feet in diameter. These seem to be xenoliths rather than segregations.

On a high hill in Sec. 13, T. 64 N., R. 3 E. is a coarse porphyritic diabase with rounded anorthosite and also fine-grained, slaty xenoliths from a few inches to several feet across. The shapes of the anorthosite inclusions and their relation to diabase are much like those of the occurrences shown in Figure 32.

On the west side of Wauswaugoning Bay, in Sec. 25, T. 64. N., R. 6 E., typical boulder-like inclusions of pure anorthosite in diabase were also noted. This is not far from the anorthosite of Pigeon Point sill, but the occurrence is more like those near Beaver Bay. The anorthosite in Wauswaugoning Bay is different in appearance from that on Pigeon Point.

Other feldspar patches in the diabase sills of the Rove area were noted north of Loon Lake, south of Clearwater Lake, and north of Pine Lake, but these are probably segregations of feldspar which formed in the sills in which they occur, as is true of the Pigeon Point sill.

[42] Grout and Schwartz, *op. cit.*
[43] F. F. Grout, "Anorthosite and Granite on Pigeon Point," *Bulletin of the Geological Society of America*, 39:562–63 (1928).

CHAPTER IV

ECONOMIC GEOLOGY

Anorthosites

Possible Commercial Uses.—The deposits of calcic feldspar, or anorthosite, of Minnesota have been known for a long time, and around 1910 attempts were made to exploit them under the misconception that the material was corundum. Although the attempt was a failure, much expensive equipment was installed for transporting, crushing, and screening the material.

Since 1929 there has been a renewed interest in these deposits because of the possibility that they might be used as a source of alumina for glass. In spite of their iron content, they are the purest large masses of feldspar known, there being no quartz and only very small percentages of other minerals in the deposits. A preliminary paper giving some of the results of recent work has been published by Schwartz.[1] There are also other uses to which this feldspar might well be adapted—this applies particularly to abrasives. Commercial deposits of soda and potash feldspar usually occur with quartz, which is undesirable in a soft abrasive. The anorthosites described in this bulletin normally contain no quartz at all, nor do they contain other hard minerals.

Considerable feldspar is used for roofing and cement surfacing. The Minnesota material, easily available in pure form and in large quantities, would seem well adapted to such use if once placed on the market. Small amounts of feldspar are also used for chicken grit, a use which anorthosite might well satisfy. This feldspar may also eventually be adapted for use in refractories and possibly as a binder for emery wheels, where its high temperature of fusion would not be particularly objectionable.

Distribution.—The distribution of the anorthosite is shown in some detail on Plates 1–5. The distribution seems entirely irregular. At a few places the feldspar masses are abundant over areas as large as a square mile. In many more areas from 40 to 160 acres will have an abundance or a predominance of anorthosite exposures. At other places extensive exposures of diabase may reveal no masses, though search will often reveal an isolated one. This may be an included fragment measured in inches or a few feet, or it may be a large mass measured in hundreds of feet. Horizontal exposures of hundreds of feet were considered large in mapping. Vertical cliffs of 50, 100, even nearly 200 feet of solid anorthosite are not uncommon.

[1] G. M. Schwartz, "The Calcic Feldspar Deposits of Minnesota," *Bulletin of the American Ceramic Society,* 16:471–76 (1937).

The total amount of anorthosite in this area must aggregate hundreds of millions of tons. Some very pure masses contain hundreds of thousands of tons, but the variability of the material in many occurrences must be taken into account in any attempt at commercial utilization.

Chemical and Mineral Composition.—The most important impurity in the anorthosite masses is iron, and unfortunately most of the associated minerals are iron-bearing, as would be expected in a rock closely associated with, and apparently derived from, gabbro or diabase masses.

The samples analyzed were picked to represent the varieties of anorthosite rather than the largest, purest masses which might develop commercial uses. Analyses 6, 7, and 8 in Table 4 (page 55) were made from large samples carefully selected to give the average of a mass rather than the composition of a lump. The iron of No. 5 has also been carefully checked by analysis of a second large-scale sample from the same mass as the original large specimen.

Tests.—Inasmuch as iron is the objectionable impurity, some preliminary tests were made to determine the possibility of eliminating the iron. The most feasible method seemed to be removal of the iron by magnetic means.

Samples of 50 to 100 pounds each were collected from three localities: (1) Split Rock quarry, coast of Lake Superior, Sec. 5, T. 54 N., R. 8 W., (2) a hill on the highway three miles northwest of Beaver Bay, Sec. 27, T. 56 N., R. 8 W., and (3) Carlton Peak, Tofte, Cook County. The samples were composed of fragments from 2 to 4 inches across. In the laboratory the entire sample was washed and dried, then chips from ½ to 1 inch were taken from the large fragments and crushed in a large diamond mortar to pass a 30-mesh screen. This crushed sample was thoroughly mixed and quartered and a sample selected for iron determination. A 100-gram sample was weighed out and screened to remove the fines. The portions between 30- and 100-mesh and between 100- and 200-mesh were run through a magnetic separator, modeled after a machine described by Hallimond[2] of England.

The tests on iron removal by magnetic means are not promising. This is due in part to the fact that olivine and pyroxene are commonly altered to serpentine and chlorite and thereby lose their slight magnetism. Microscopic examination of the purest material reveals so little iron-bearing mineral that it has been suggested that some of the iron may be isomorphous with the other elements of the feldspar molecule. The relative sizes of atoms suggest that ferric iron is isomorphous with aluminum, rather than ferrous iron with calcium.

The following is a summary of the results of tests made in the Geology Laboratory of the University of Minnesota:

[2] A. F. Hallimond, "An Electromagnetic Separator for Mineral Powders," *Mineralogical Magazine,* 22:377–81 (1930).

SPLIT ROCK QUARRY SAMPLE

Sample crushed to pass 30-mesh showed Fe_2O_3=0.47 per cent.

Portion through 30-mesh retained on 100-mesh, run over a magnetic separator; nonmagnetic fraction showed Fe_2O_3=0.44 per cent.

Portion through 100-mesh retained on 200-mesh; nonmagnetic fraction showed Fe_2O_3=0.43 per cent.

Sample through 60-mesh retained on 100-mesh showed Fe_2O_3=0.41 per cent.

Portion boiled in HCl showed Fe_2O_3=0.27 per cent.

SAMPLE FROM SE¼ SEC. 27, T. 56 N., R. 8 W.

Sample crushed to pass 30-mesh showed Fe_2O_3=0.53 per cent.

Portion through 30-mesh retained on 100-mesh; nonmagnetic fraction showed Fe_2O_3=0.52 per cent.

Portion through 100-mesh retained on 200-mesh; nonmagnetic fraction showed Fe_2O_3=0.53 per cent.

CARLTON PEAK SAMPLE

Sample crushed to pass 30-mesh showed Fe_2O_3=0.75 per cent.

Portion through 30-mesh retained on 100-mesh; nonmagnetic fraction showed Fe_2O_3=0.66 per cent.

Portion through 100-mesh retained on 200-mesh; nonmagnetic fraction showed Fe_2O_3=0.74 per cent.

At the request of the director of the Minnesota Geological Survey, the United States Bureau of Mines undertook magnetic and flotation tests on samples of the Split Rock feldspar. The report is as follows:

The sample received was anorthosite feldspar, showing slight surface alteration in part. The rock is gray with inclusions of fine-grained magnetite and ferromagnesian minerals of the pyroxene group, occurring chiefly in small dark aggregates. About 2 per cent of the sample seemed to be these dark minerals. Examination of the dark areas under the binocular microscope showed small distinct grains of dark mineral, and also darkened anorthosite without distinct mineral particles. There was apparently some alteration of dark minerals to serpentine and chlorite, and a slight limonite staining on original exposed surfaces.

The object of the testing was the reduction of the iron oxide content to at most 0.25 per cent and to less than 0.15 per cent if possible, to permit use of the rock for glass making.

Thorough analyses, microscopic examinations, and magnetic separation tests had already been made by the sponsors of the project on material of which the present sample was a part. The information was published under the title "The Calcic Feldspar Deposits of Minnesota" by G. M. Schwartz in the *Bulletin of the American Ceramic Society*, vol. 16, no. 12, Dec. 1937.

Analyses at Rolla were confined to determining the iron oxide content of the sample and the test products. The head sample assayed 0.50 per cent Fe_2O_3.

Screen analysis of material crushed through 4-mesh indicated some concentration of iron oxides in the minus 28-mesh portion, with most in the minus 200-mesh fraction. However, microscopic examination indicated good liberation of the dark minerals at 65-mesh.

A portion of the sample was crushed through 65-mesh, and the minus 200-

mesh material removed by screening. The −65, +200-mesh material was 77 per cent of the original weight taken.

After treatment on the laboratory high intensity magnetic separator the residual 65- to 200-mesh material was 73 per cent of the original weight and contained 0.42 per cent of Fe_2O_3. Apparently the liberated magnetite had been removed. The residue contained free grains of nonmagnetic dark minerals.

The residual 65- to 200-mesh material was ground through 200-mesh and treated on the laboratory ferro-filter and about 2 per cent by weight removed as magnetic concentrates. The tailings still contained 0.39 per cent of Fe_2O_3.

Flotation tests were made on minus 200-mesh material. It was attempted to concentrate the iron-bearing minerals. About 23 per cent of the charge was floated. The tailings contained 0.42 per cent of Fe_2O_3.

Other flotation tests were made on 65- to 200-mesh nonmagnetic residue from the first magnetic separation tests. A visible concentration of dark minerals was obtained, but the tailings contained 0.39 per cent of Fe_2O_3.

When the 65- to 200-mesh nonmagnetic material was ground through 200-mesh, deslimed and treated by flotation, tailings containing 0.37 per cent of Fe_2O_3 were obtained. Grinding through 325-mesh and flotation treatment gave no better results.

The reagents used for flotation were Quebracho extract for dispersion and conditioning and oleic acid for collecting the dark minerals. In some tests cresylic acid was used as an additional frothing agent.

In all the flotation tests a good concentration of dark minerals was obtained. Apparently the iron oxide content of the flotation tailings was either in extremely fine-grained unliberated dark minerals or present as an iron replacement of the lime or alumina contents of the anorthosite.

Neither magnetic separation nor flotation was successful in reducing the iron content to the desired limits. Apparently the removal of the dark minerals by flotation was quite complete but iron was still contained in the anorthosite and could not be removed in a separable form.

Black Sands

Local concentrations of black sands occur along the north shore of Lake Superior. Thus Black Bay (see Plate 1), a small bay three miles southwest of Beaver, received its name from the black sands.[3] There has been a good deal of speculation as to the possible value of these sands. They are derived from the weathering of the abundant igneous rocks of the region and may be expected to carry only the elements found in the rocks themselves. This means that the principal constituents are magnetite (Fe_3O_4) and ilmenite ($FeTiO_3$).

Robert Calton, a graduate student at the University of Minnesota, has made a study of the sand from Black Bay to determine the possibility of separating the ilmenite from the magnetite and other minerals. A screen analysis of this sand is as follows:

[3] N. H. Winchell, *Preliminary List of Rocks* (Ninth Annual Report of the Geological and Natural History Survey of Minnesota, 1880), p. 24.

Over 9-mesh	4 per cent
9 to 16-mesh	26
16 to 32-mesh	49
32 to 60-mesh	20
Under 60-mesh	1
Total	100

A mineral analysis based on a microscopic study of mounted and polished grains gave the following results:

Free magnetite	5 per cent
Titaniferous magnetite	32
Titaniferous magnetite-silicate	8
Free ilmenite	16
Ilmenite-silicate	1
Other minerals, chiefly silicates	38
Total	100

It was found that a relatively pure ilmenite concentrate could be made by use of a dry magnetic cobber as well as by use of a small laboratory separator. If large deposits were available, these preliminary tests would be worth following up, but the only deposits known along the Minnesota coast are very small.

Building Stones

Only a small amount of stone has been quarried in this area, and that for local use. The absence of railroads and of proper loading facilities for water transportation has discouraged use of the various rocks. Aside from the anorthosite the principal rock with seeming possibilities is the coarser facies of the Beaver Bay diabase. This was quarried some years ago at the northeast headland of Beaver Bay for use in the breakwater at Two Harbors. Another quarry was opened by the Gooseberry camp of the Civilian Conservation Corps, along the highway about a mile southwest of Beaver Bay, to obtain coarse black rock for various masonry uses at the Gooseberry State Park. Some of this diabase gabbro seems to have possibilities for use as so-called black granite.[4] It will take a polish and seems to occur with widely spaced joints at places. More investigation of its possibilities is needed.

Most of the other igneous rocks do not appear to have the special qualities necessary to make desirable quarry rock. However, a few buildings at Duluth use diabase, red rock, and intermediate rock, forming a unique color mixture.

Rock suitable for crushing may be found throughout the area, but the relative abundance of gravel has made this use unnecessary.

[4] G. A. Thiel and Carl Dutton, *The Architectural, Structural, and Monumental Stones of Minnesota* (Minnesota Geological Survey, Bulletin 25, 1935), p. 110.

Mineral Prospects

In view of the abundant occurrence of copper in the Keweenawan rocks of the south shore of Lake Superior, it is rather surprising that so little copper is found in the rocks of the north shore. This scarcity applies particularly to the area covered by this report. In spite of the careful examination of all of the rock exposures which could be located, no copper or other mineral deposits of interest were found. Small carbonate veinlets along the shore of Lake Superior show green copper stains at scattered points.

Winchell[5] notes that a soft, reddish amygdaloidal bed northwest of Beaver Bay in SE¼ Sec. 2, T. 55 N., R. 8 W. was explored for copper by test holes and trenches. A shaft about 400 feet south of E¼ cor., Sec. 9, T. 55 N., R. 8 W. was sunk in an ophitic basalt with some amygdaloidal material. The reason for this shaft is not evident from the dump, which shows no special mineralization.

Conspicuous quartz veins, up to perhaps one foot wide, cut the traprock hill in NE¼ SE¼ Sec. 8, T. 58 N., R. 6 W. Some of the vein-filling is smoky and amethystine quartz, but most is white and seems to hold no valuable minerals.

[5] *The Geology of Minnesota* (Final Report of the Geological and Natural History Survey of Minnesota), Vol. 5 (1900), p. 188.

CHAPTER V

TOWNSHIP DESCRIPTIONS

Detailed maps of each township are shown in Plates 1–5 and should be referred to in reading the township descriptions.

TOWNSHIP 54 NORTH, RANGE 8 WEST (PLATE 1)

Locations.—This township is a small triangular area left by township and range lines along the lake. Locations were determined by pacing and sun-compass traverses from the highway. The forty lines on the highway were located by using the section line between Sections 5 and 6, which had recently been resurveyed and staked at the section and forty corners. The shore line of Lake Superior was carefully mapped by pacing from the meander corner between Sections 5 and 6, and is much more accurate than that on other maps.

Surface Features.—The name Split Rock was applied to the river and adjacent area, probably from the appearance of the two large white anorthosite hills, which as seen from the lake give the appearance of having been split apart. Upham[1] states that the name refers to the rocks at the mouth of the river, probably incorrectly, as the river has a wide gravel deposit at its mouth.

This township furnishes a good illustration of the irregularity of the shore line. The most westerly portion has a considerable indentation or bay at the mouth of the Split Rock River. This bay is clearly the result of the submergence of the fairly wide valley of the river, which has eroded the lava flows rather severely in its lower course. In the southeast portion of Section 6, another bay just northeast of the mouth of the river evidently owes its existence to wave erosion of a weak zone in the flows. The rather straight sides of the point separating these bays is suggestive, particularly in contrast to the normal strike, the latter being nearly parallel with the coast, and the strike here at right angles. Local faulting or other structural disturbance is evidently responsible.

A fairly deep little bay lies between the two large anorthosite masses of Section 5. The superior resistance of the anorthosite to erosion resulted in the points or headlands on each side of the bay. (See Figure 45.) The larger bay at Little Two Harbors, one of the most picturesque spots on the shore, owes its formation to the erosion of softer rocks back of a resistant basalt flow. The coast in general is low except at the two anorthosite hills.

The inland area slopes gently toward the lake, coinciding in general with the direction of dip of the rocks.

[1] Warren Upham, *Minnesota Geographic Names* (Collections of the Minnesota Historical Society, Vol. 17, 1920), p. 76.

Geology.—So far as can be determined, Sections 6 and 7 are entirely underlain by basalt flows, which are extensively exposed along the coast and stream valleys. Two flows are exposed southwest of the Split Rock River in Section 7. Farther west in T. 54 N., R. 9 W. is one of the large areas of felsite flows on the Minnesota coast. The point east of the river is apparently one thick basalt flow, and the hill in the west half of Section 6 is formed by a thick red ophitic flow.

The small area of Section 5 shows an unusual variety of significant geologic features. In Crazy Bay an ophitic flow is continuously exposed almost to the southerly large anorthosite mass, but weathered diabase occurs between the flow and the anorthosite. To the northeast, at Little Two Harbors, the point and shore to the east are composed of dense basaltic rock with a dip of 9° to the south. Back of the bay are exposures of diabase which seem to be a part of the diabase intrusive, and at places small patches and blocks of anorthosite are embedded in the diabase, but these are fragments not phenocrysts. This coarse diabase is extensively exposed along the shore near the anorthosite masses. It is probable that these exposures represent the farthest southwest extension of the Beaver Bay diabase.

The anorthosite exposures in this area are probably the best known of any of these peculiar masses, and this is the most instructive place along the shore to study them. They range in size from single crystals to the enormous mass at Split Rock Point, which has a length of over 500 feet, a width about half as great, and a sheer exposure extending some 200 feet above the lake. Some years ago a quarry and crushing plant were established at the west side to produce abrasive, but evidently the discovery that the material was feldspar ended the scheme. This mass is very pure feldspar, as is shown by analysis 7 in Table 4.

Alongshore between the two knobs is a complex of anorthosite blocks of various sizes embedded in diabase. The contacts are invariably sharp, with the diabase clearly intruding the anorthosite and forming a matrix. The inclusions are characteristically rounded, as is true of most of these masses. The several anorthosite masses differ considerably, some fine, some coarse, with crystals up to six inches in length. The ferromagnesian minerals are concentrated in certain layers, so that the masses are distinctly banded. On a low hill just above the southwest corner of the bay, an anorthosite breccia with granulated anorthosite matrix shows up conspicuously on the weathered surface.

Township 55 North, Range 8 West (Plate 1)

Locations.—The outcrops and other features in this township were located almost exclusively by reference to north-south traverses, spaced at quarter-mile intervals. This work started from the highways, along which the locations had been marked by reference to road surveys or by traverses from known points with a stadia rod. Corners at which stakes or bearing trees were found are shown on the map.

Surface Features. — The most conspicuous surface feature of this township is the long, rocky, homoclinal ridge of Beaver Bay diabase (Figure 43) with several high anorthosite knobs projecting above the general level. The shore line of Lake Superior as shown on Plate 1 was carefully mapped and indicates the outline better than any other map. Except in detail the shore is relatively straight, probably because the Beaver Bay diabase is continuous from Rusty Point in Section 33 to Beaver Bay in Section 12. Except at Split Rock lighthouse and the southwest headland

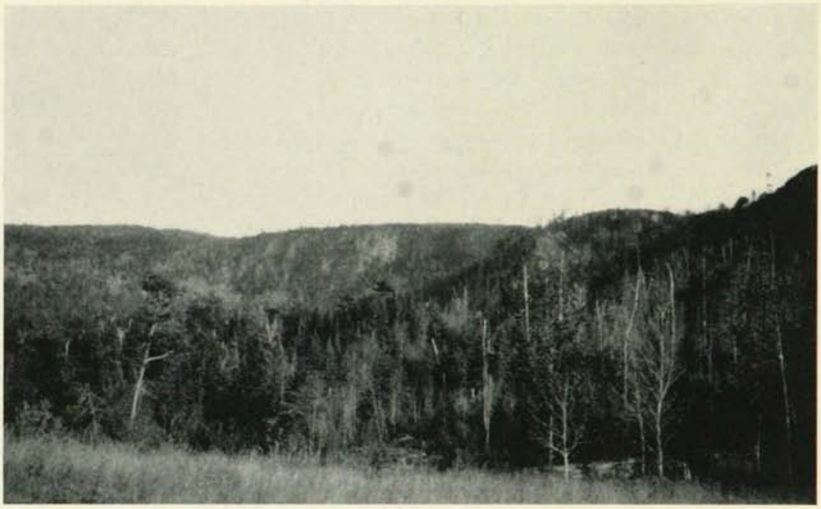


FIGURE 43. — Portion of a northwest-facing escarpment of Beaver Bay diabase. Its appearance is characteristic of diabase ridges throughout the area.

of Beaver Bay (see Figures 2 and 44) the coast, although rocky, is relatively low and the dip of the diabase carries it beneath lake level. Rusty Point is named from the reddish granite that forms a small point on the shore.

Back of the shore the Beaver Bay diabase forms a rocky area which rises gently to the northwest and terminates in a series of high, northwest-facing escarpments overlooking the valley of the West Beaver River. (See Figure 43.)

The northwest portion of the township, along the valley of the West Beaver River, is notably flat for this district and has few rock exposures. The red clay characteristic of the deposits of glacial Lake Duluth shows conclusively that the valley of the Beaver is largely preglacial in origin and was occupied by an arm of the glacial lake. The exposures of bedrock in this level area are mainly basalt flows. In Section 9, where a large dike trends north from the main mass of the Beaver Bay diabase, the valley narrows greatly.

It is noteworthy that where stream valleys are eroded in flows, they are usually much broader than where they pass over areas of the resistant diabase, but there is a rather conspicuous exception in the flows of Sections 17, 20, and 29 and portions of adjacent sections. A long series of exposures form a homoclinal ridge, bounded in general on the northwest by an escarpment, and with a broad, gentle back slope extending to the southeast, where a creek valley masks the contact with Beaver Bay diabase. The homoclinal ridge contains a thick porphyritic flow, which is amygdaloidal with large agates on the back slope.

The east branch of the Beaver River also has a broad valley filled with glacial-lake clay, which is evidently thick, as the river and its tributaries do not cut through it at most places. It is noteworthy that in the last mile of its course the Beaver River has eroded a narrow, rocky gorge with many rapids and falls. (See Figure 6.) This seems to prove that the main part of the Beaver valley was determined by a base somewhat higher than the present level of Lake Superior. The Beaver River drops 300 feet from the line between Sections 11 and 12 to its mouth, a distance of a mile as the river flows. Above that point it drops only 198 feet for the five and one-half miles beginning at the bridge in Section 17.

One of the most interesting physiographic features of this area is the occurrence of two transverse valleys or gorges cutting the diabase escarpment. They extend from near the Beaver River in Section 9 to the small stream which empties into Lake Superior at Black Bay. (See Plate 1.) The cliffs along the sides of these gorges are steep and high (750 feet above Lake Superior). An indistinct divide now separates small streams flowing in opposite directions. The north-flowing streams of these gorges empty into the Beaver River. The gorges evidently belong to an earlier cycle of erosion than the upper valley of the Beaver River, which is here filled with the sediments of glacial Lake Duluth. Thus the Beaver River and its tributaries seem to furuish evidence of three partial cycles of erosion. The earliest cycle, represented by the small valleys just described, is not necessarily preglacial, but is earlier than the second cycle, which established most of the Beaver valley as it exists today. This second cycle is earlier than the Superior Lobe of the Late Wisconsin glaciation. The gorge of the last mile of the river represents the postglacial cycle of erosion, which has also entrenched the river somewhat in the glacial-lake clays of the upper valley.

A rather steep slope with some southeast-facing cliffs interrupts the gentle slope toward Lake Superior in Sections 14, 15, and 22 west of Highway No. 61. Wave-cut cliffs recognized at several places indicate that the steep slope is probably one of the more pronounced shore lines of glacial Lake Duluth.

Geology. — By far the most conspicuous geologic feature of this town-

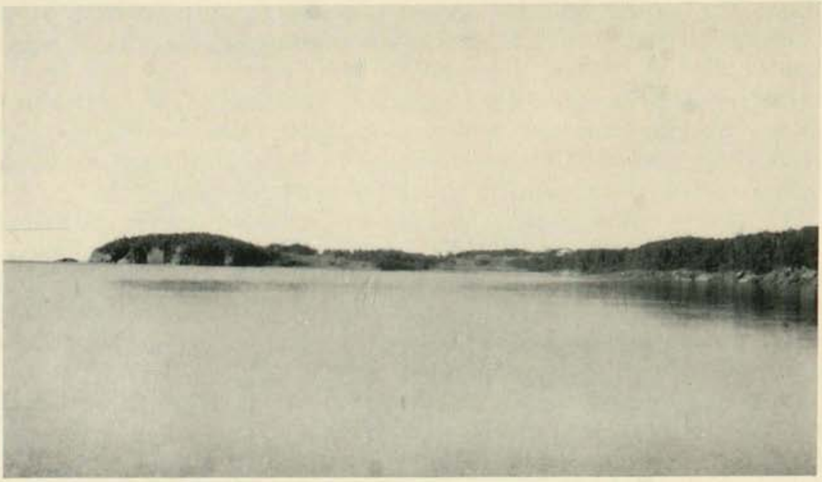


FIGURE 44. — Felsite headland, Beaver Bay, Lake Superior.

ship is the extensive Beaver Bay diabase sill with associated anorthosite masses. Alongshore this rock is almost continuously exposed from Rusty Point to Beaver Bay. Inland for various distances exposures are numerous. The general features of this diabase have been described above (pages 32–40).

The general relation of the anorthosites to the diabase is brought out by Plate 1. They are grouped along the escarpment that overlooks the Beaver valley. Exposures of flows on the river and near the foot of the escarpment indicate that the base of the sill is somewhat above and south of the river. Far to the southwest there are large exposures of diabase in Sections 32 and 33. They form a ridge that terminates in the high anorthosite cliff on which the Split Rock lighthouse stands. This diabase is probably a local offshoot of the main Beaver Bay sill. The shore cliff northeast of the lighthouse shows the diabase resting on flows, with blocks of anorthosite in the dense chilled diabase. (See Figure 33.) Section 28 has extensive exposures of the main part of the Beaver Bay diabase, here very coarse, especially along the highway near the west section line. The mottling is about as coarse as that of any diabase or gabbro on the north shore of Lake Superior. (See Figures 26 and 27.) Anorthosite is confined to the western portion of the section, and none is found within a mile of the shore between Section 28 and Beaver Bay.

In Section 22 near Black Bay there is a gradual change from the coarsely mottled diabase on the west to a coarse, granular diabase on the east. (See the analyses in Table 2.) Black Bay receives its name from the abundant magnetite-ilmenite sand of the beach. The darker diabase east of Black Bay contains olivine and weathers readily to a rusty, gravelly rubble. The coarsely mottled diabase occupies all of the eastern portion of Section 21. The western portion contains numerous anorthosite masses, some as large as 150 feet wide and 300 feet long.

In Section 16 an extremely rugged area of diabase is cut by transverse valleys, exposing large masses of coarsely mottled diabase. The cliff along the east side of these valleys is conspicuously jointed, the principal joints striking northeast and dipping about 70° to the south.

The prominent ridge of the diabase, which extends northward through Section 4, is evidently a large dike. Its connection with the main mass of the Beaver Bay diabase is eroded and covered by the clays of the valley of the Beaver River. This diabase is coarse but not mottled, and no anorthosite inclusions were found in it except a single angular one near the north end.

The bluff overlooking the valley of the Beaver River in Sections 10 and 11 consists of coarsely mottled diabase near the top with coarse segregations of pyroxene and feldspar common. Almost horizontal banding was noted in it near the east side of Section 10. In Section 11 both felsite and basalt flows are exposed near the foot of the escarpment, indicating that the bottom of the Beaver Bay sill is roughly near the base of the bluff along the river, though concealed at most places by talus. This is significant, indicating as it does a concentration of anorthosite near the base of the Beaver Bay sill rather than at its top, as might be expected from the fact that plagioclase feldspar is lighter than average diabase. The bluff in Section 11 is composed of coarsely mottled diabase, but about 300 paces south of the center the coarse basic type occurs.

Along the shore in Section 14 are practically continuous exposures of diabase, much of which shows a conspicuous jointing into large blocks. Nearly horizontal joints have a slight dip toward the lake. Horizontal banding is marked at the rocky point, and at places some orientation of the feldspars occurs parallel to the sheeting which dips gently toward the lake.

Section 12 and the small fragment of Section 13 include the town of Beaver Bay and the mouth of the Beaver River, which empties into Beaver Bay. This area includes a complex series of igneous rocks with diabase predominant.

Southwest of Beaver Bay there is a long, continuous exposure of diabase along the lake shore. (See Plate 1.) The westerly exposures are coarse black olivine diabase, whereas those to the east are of the coarsely mottled, more feldspathic type. These are the first exposures of mottled diabase alongshore east of Section 37.

The southwest headland of Beaver Bay is composed of a series of rocks (see Figure 45), but doubtless the resistance of the diabase and anorthosite is the reason for its existence. Facing the lake is a high diabase bluff with one large and several smaller anorthosite masses. Back of this is a rhyolite. In the bay at the mouth of the river is a rhyolite, which

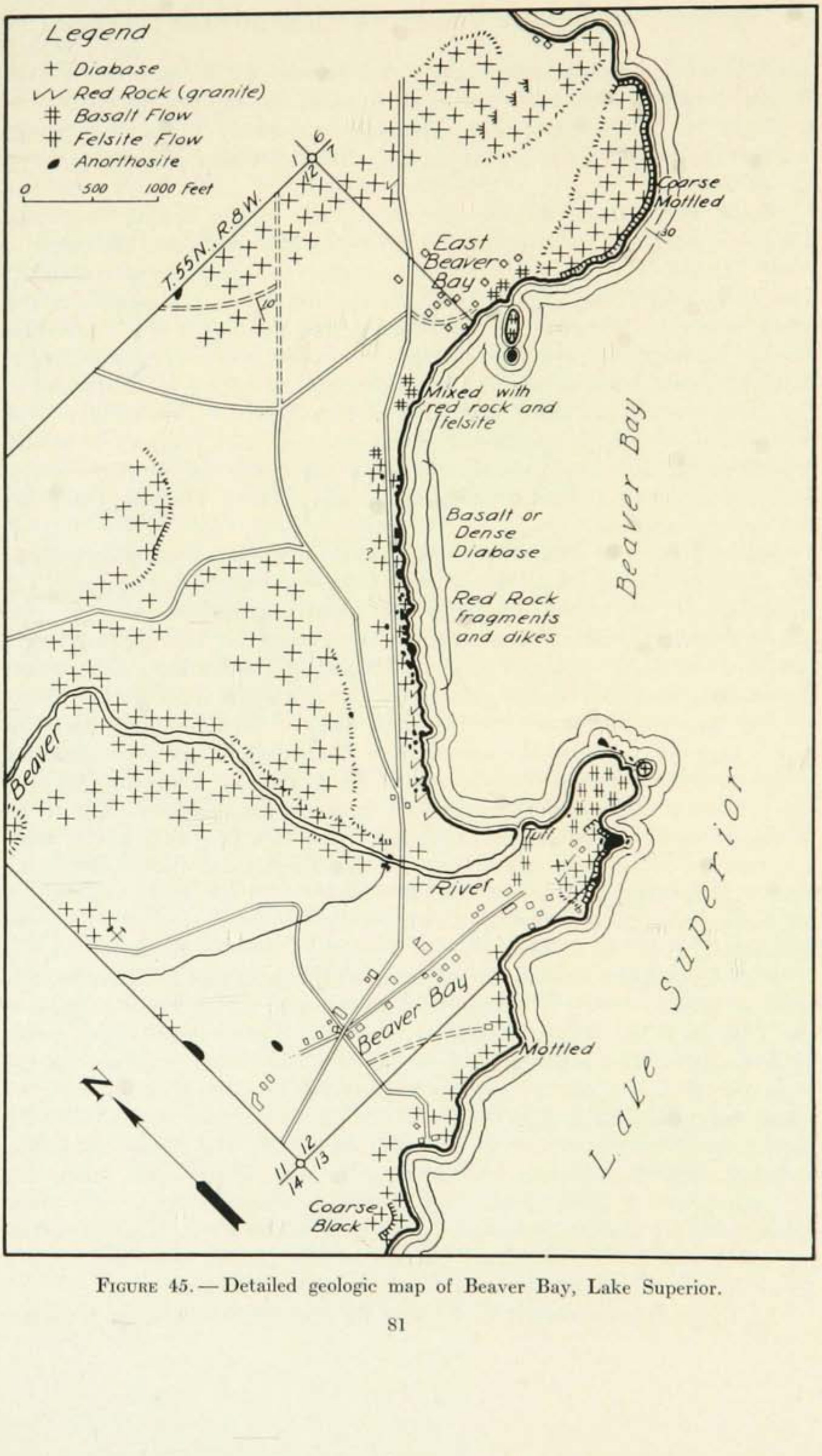


FIGURE 45.—Detailed geologic map of Beaver Bay, Lake Superior.

is well bedded, possibly tuffaceous, and strikes N. 30° W. and dips 8° NE. It should be noted that this series of rhyolites has diabase on both sides and may be composed of large included fragments. Similar rhyolite is exposed on small islands across the bay, also on Cedar Island northeast of the bay.

Below the highway bridge near the mouth of the Beaver River the diabase is coarsely mottled and has xenoliths of anorthosite and dikes of later diabase. The northeast end of the gravel beach has a red felsite breccia in which are large anorthosite boulders. The relations are confused. Some red material cuts anorthosite, and a 4-foot block of anorthosite lies between red breccia and basalt. Some basalt seems to have amygdaloidal facies, but has anorthosite inclusions, and may be analagous to the exposures on the shore northeast of Encampment Island. In a little bay with a steep wall, anorthosite seems to occur in a complex of basalt, felsite, and diabase. One small cove has a northeast wall of rhyolite and a southwest wall of diabase and impure anorthosite. The rhyolite overlies dense basic rock.

Other masses of anorthosite, large and small, occur at places along the shore of the bay, with dense chilled diabase overlying them and the whole cut by red dikes. Amygdaloidal basalt is exposed near the east gravel beach. A black anorthosite was excavated for the highway. (See analysis 8 in Table 4, also Figure 22.) North of the highway is a 20-foot rounded mass of anorthosite enclosed in dense diabase. (See Figure 34.)

The anorthosite masses exposed in Beaver Bay probably show as much variety as any in the entire area. They range from pure, greenish white, transparent rocks to the coarse black rock in which the feldspar has abundant inclusions of magnetite and pyroxene. The masses range in size from 1-inch fragments, through those of a few feet, up to those 100 feet across. The rounded, boulder-like masses are particularly well shown. In general the most abundant anorthosites are in the coarse diabase along the middle stretch of the shore of the bay, although they are also found in dense diabase near the mouth of Beaver River.

This township contains several areas of Keweenawan red granite. The most accessible occurs between the highway and Rusty Point in Section 33. This rock has a nearly normal granitoid texture with considerable visible quartz. The remainder of the rock is chiefly red feldspar. On the west side of the point the granite appears to be part of a sill lying on dense amygdaloidal basalt, but on the north side it lies on diabase with the contact striking N. 30° E. and dipping 35° S. The diabase is dense, possibly chilled, and may possibly be later than the granite. Along the bay northeast of Rusty Point red granite is exposed, apparently lying beneath coarse diabase, which is locally banded with long feldspars striking north-south. The southeast contact of the granite is a fault with a strike N. 80° E., dip 80° N., and nearly vertical slickensides.

At the northeast corner of Section 32 and one-fourth mile west are two prominent hills of granite like that at Rusty Point. Abundant exposures of diabase and flows show that they are not connected with the rock at Rusty Point. The only other red granite exposure in the township is that along the shore of Beaver Bay, where small amounts are mixed in confusion with other rocks, some fragmentary and some apparently intrusive.

The large, relatively level area in Sections 5, 6, 7, 8, 17, and 18 and portions of 4, 9, and 19, as noted above, is mainly underlain by basalt flows, although they are only locally exposed. In Section 6 are small exposures of fine-grained diabase, probably intrusive. The scant exposures in Section 5 consist of weathered ophitic flows. In Section 7, along the east branch of the Beaver River, basalt with amygdaloidal zones indicates at least three flows. A few small exposures of flows occur in Section 8, and near the west quarter corner a dense diabase dike about 10 feet wide crosses the river, striking about N. 20° E. In the northwest quarter of Section 19 is a low ridge with exposures of an ophitic flow which has an amygdaloidal portion on the southeast.

The extensive series of basalt exposures extending from Section 31 northeastward to Section 16 are probably parts of one thick porphyritic flow, which strikes about N. 45° E. and dips 5° SE. It has large, scattered agate amygdules on the glaciated surface. Exposures of the porphyritic flow are particularly abundant in the northwest part of Section 29, and the southeastward slope appears to coincide with the 9° dip over large areas. This area breaks off in a northwest-facing escarpment, where the river has eroded across it.

Both branches of the Beaver River have eroded their valleys in the flows. The exposures near the east side of Section 10 are dense fresh basalt, somewhat amygdaloidal at places, and cut by numerous dikes from 6 inches to 3 feet in width.

Several basaltic rocks are exposed along the highway between Sections 2 and 3. Near the north side of Section 2 the East Beaver River has eroded a small gorge in the flows with a series of three picturesque falls. At the lower falls a good amygdaloidal zone is exposed.

This township contains some of the most extensive occurrences of anorthosite on the north shore. As is clearly brought out by the map (Plate 1), these masses are closely related to the Beaver Bay diabase. Those at Beaver Bay are best known and have already been noted in the above description of the geology of that bay (page 82). Others are noted here. One of the most instructive exposures is northward along the cliff from Split Rock lighthouse. Numerous rounded boulders of anorthosite are embedded in the diabase at or near the base of the sill. (See Figure 33.) Near the lighthouse much larger masses of anorthosite occur. Some of these masses are very pure, others show a sort of diabasic anorthosite. The anorthosite on which the lighthouse stands shows a conspicuous banding, which strikes N. 70° E. and dips 70° S.

In Section 22 rock exposures are not so abundant as in the area to the northeast, but the resistance of the anorthosites to erosion causes them to stand out where the other rocks are covered. Most of the masses are fairly pure, but one large mass and some of the smaller ones show many patches or spots carrying iron minerals.

The stake at the quarter corner between Sections 28 and 33 is at the top of a high anorthosite hill with a 100-foot cliff facing south. The mass is fully 200 feet wide and 300 feet long. It consists of a normally coarse, pure anorthosite. Diabase is exposed at the base as if the anorthosite was a flat mass capping the hill. A similar but somewhat smaller mass occurs about one-fourth mile to the north.

A series of about fifty anorthosite masses occur along the west side of Section 21. Since the area is brushy, it is probable that there are many others which were not seen. The largest masses are in the northwest quarter and measure fully 300 feet across. Some are fine-grained, others are of the more normal coarse type; most of them are fairly pure, but the largest mass — the one farthest northeast — is specked with ferromagnesian minerals. One of the most extensive occurrences of anorthosite in a limited area is that in the southwest quarter of Section 10, where a high bluff overlooks the valley of the Beaver River. This bluff includes several large masses of anorthosites and many smaller ones. Near the base, more or less red rock occurs with the diabase, and forms a matrix to some of the anorthosite blocks, a rare association in the anorthosites of Minnesota. At places anorthosite is exposed over a vertical extent of nearly 200 feet.

In the southeast quarter of Section 10 are several small masses and one large mass of anorthosite associated with very coarsely mottled diabase. Some of these contain numerous rusty areas of ferromagnesian minerals with a suggestion of diabasic texture. The large mass has a dome-like surface 100–150 feet wide and 650 feet long, with possibly one or two interruptions of diabase. It appears to be very pure feldspar.

In Section 11 anorthosite is rather widely scattered. The large masses are near the top of the bluff facing Beaver River. Small inclusions, down to the size of single crystals, occur in the western part of the section. The anorthosite is associated with the coarsely mottled diabase and not with the more basic facies along the south line of the section. Near the center of the section is a very large mass of fairly pure anorthosite with a dome-shaped top. It is about 650 feet long in a northwest-southeast direction and has a maximum width of 250 feet. Smaller masses surround it; these show much brecciation of the feldspar, as do the borders of the main mass. A smaller mass about one-fourth mile northeast of the large mass is composed of much darker anorthosite.

Section 1 has several scattered anorthosite masses in the prevailing diabase, but most of these are relatively small. They differ considerably, some being pure, others impure; there is also a variety in coarseness of grain.

FIGURE 46. — Low glaciated island of anorthosite and diabase, Beaver Island, Lake Superior.

The Beaver Bay diabase is very massive and has been quarried to a small extent. The northeast headland furnished a considerable amount of massive rock a few years ago for breakwater construction at Two Harbors. More recently a quarry was opened on Highway No. 61 about a mile and a half southwest of Beaver Bay for use in construction work at Gooseberry State Park. The massive character of the diabase at places alongshore between Split Rock and Beaver Bay suggests that it might be used to furnish coarse diabase (black granite) for polishing. Water transportation by barge could no doubt be used.

TOWNSHIP 55 NORTH, RANGE 7 WEST (PLATE 1)

Locations. — Several recently established corners were found in this fragment of a township, and property lines are all well marked along the lake and highway.

Surface Features. — The most prominent feature of this small area is the northeast headland of Beaver Bay, which is a high diabase bluff. The coast beyond is low, fairly straight, and rocky. The islands about one-fourth mile off shore are among the few along the entire Minnesota coast. Beaver Island (Figure 46) is the largest.

Geology. — Most of the small area of this township is underlain by Beaver Bay diabase. Alongshore in the southwest portion of Section 6 this rock is coarse-grained with scattered olivine spots about half an inch across, which weather out on exposed surfaces. To the northeast sheeting

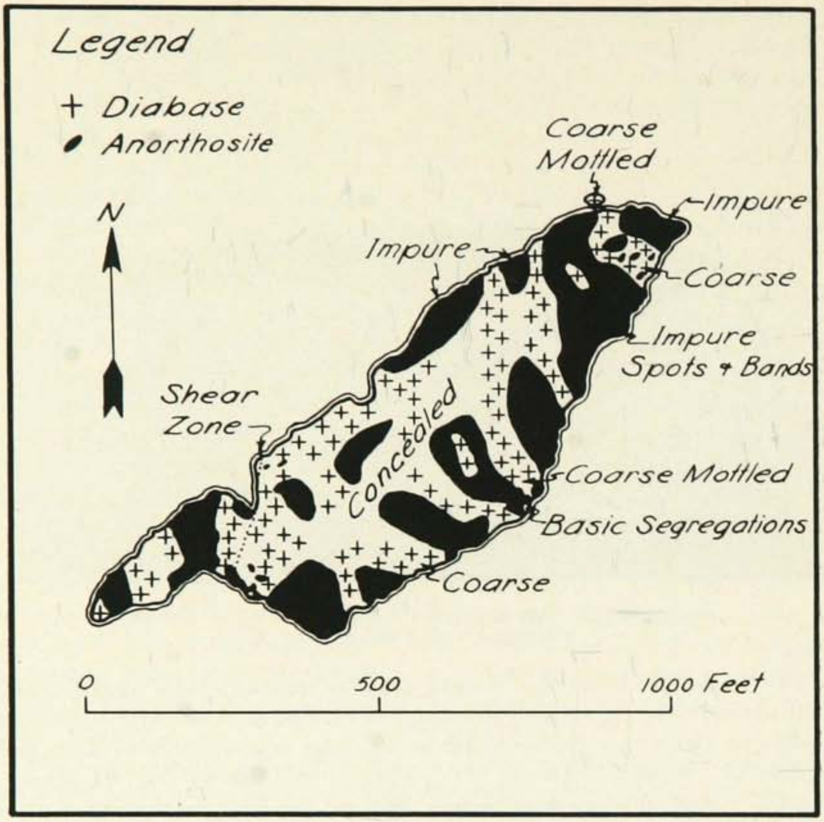


FIGURE 47. — Geologic map of Beaver Island, Lake Superior. The black is anorthosite; crosses represent diabase.

seems to indicate that the rocks strike N. 35° E. and dip 10° SE. The coarsely mottled diabase makes up most of the exposures. The exposures at the headland of Beaver Bay consist of very coarsely mottled diabase, which on the bluff facing the lake shows bands that strike about north-south and dip 30° to the east.

Beaver Island (Figures 46 and 47) is composed of a confused mixture of anorthosite and very coarsely mottled diabase. Part of the anorthosite is fairly pure but most is very impure, the impurities forming oval spots, impure bands, and irregular masses approaching diabase in composition. The diabase shows many coarse segregations of plagioclase and pyroxene.

Cedar Island is composed entirely of rhyolite. Small quartz phenocrysts show up well on a fresh fracture. Between Cedar Island and the shore a series of rocks and shoals are composed of coarsely mottled diabase. However, in Beaver Bay (Island Number One) a rough, irregular rock mass is composed of porphyry exactly like that of Cedar Island.

Anorthosite is not common in this fractional township, although exposures are excellent, and anorthosite occurs in abundance to both the southwest and the northeast along the shore. This fact serves to emphasize the very irregular distribution of these rock masses. However, the northeast portion of Section 6 contains several large masses. The largest is fully 300 feet long and more than 200 feet wide and is a fairly pure, transparent, greenish variety. Smaller masses occur near this, and there is also a series of small masses at the meander corner between this township and the one to the north. These masses may be considered southwest outliers of an extensive series extending north and east.

Township 56 North, Range 8 West (Plate 2)

Locations.—Most of this area has been burned over at least once, and so many of the original survey marks have been destroyed that few corners were found except near the highways; these are shown by circles on Plate 2. Stadia surveys were made along the main highway, and traverses either east and west or north and south were made at quarter-mile intervals. All features are fairly accurately located except where the distances from known points are great, as in Section 3 and portions of Sections 24, 25, and 36.

Surface Features.—The southern third of the area mapped is much like T. 55 N., R. 8 W., previously described. It is a rugged area with high diabase ridges cut transversely by the Beaver River. In Section 34 a high, broad diabase ridge marks the northward continuation of the large dike of Sections 3 and 4 of the township to the south. Whether or not this dike ends in Sections 23 and 26 is not certain, because the Beaver valley cuts abruptly across it, but exposures to the north suggest its continuation, though with a narrower width.

Sections 35 and 36 show a series of four east-west striking homoclinal ridges, some caused by resistant flows whose southerly back slopes show approximately the dips of the flows. To the north in Section 25 and extending into 26 is a very high, rugged diabase area much dissected by erosion. Section 24 is mainly occupied by a flat-topped hill of diabase. The high area continues into Section 24, thence trending northeast into the adjacent township. Twin Lakes occupy a particularly deep gorge, probably representing a stream canyon of an earlier cycle of erosion.

Sections 13, 14, 15, 22, and 23 form a rather level and partly swampy area out of which rise several sharp, rocky hills, mainly diabase. The soil along the Beaver River as far up as Section 22 indicates that glacial Lake Duluth extended at least that far. Lax Lake, a long, narrow, mostly shallow lake, also appears to occupy a stream valley whose drainage was disturbed by the last glaciation. The hills south of Lax Lake mark the termination of the sharp rise of the general level from Lake Superior. To the north and northwest of Lax Lake the topography is much less rugged, rock exposures are fewer, and minor streams flow in broad and frequently swampy valleys. In general the country is slightly higher at the north. Some of the streams have cut narrow gorges in the rock ridges. Most of the rock exposures are homoclinal ridges with a general east-west strike, and a general summit level that is frequently referred to as the Laurentian peneplain.

Geology.—The large ridge of diabase in Section 34 is evidently a dike. Evidences of its dike-like character are the relatively steep bluffs on each side, with flows known to exist in the level areas, and the trend across the regional trend of the sills and flows. The diabase is mainly the coarsely mottled variety. It is probable that the mass was connected with a sill-like mass in Sections 27 and 26, but the continuity is broken by the East Beaver River.

Section 25 and adjacent areas are occupied by an extremely rugged mass of diabase with extensive anorthosite occurrences. The large bluff on the south side of Twin Lakes is a notable red ophite flow. At the base of the bluff along the north shore of lower Twin Lake there is an excellent exposure of the only sedimentary rock known within five miles. This is a well-indurated arkose with good bedding and cross-bedding. The strike is S. 80° W. and the dip 17° S. Thin sections show that it consists largely of rounded grains of plagioclase feldspar.

Sections 35 and 36 have very extensive exposures of flows, which are more or less isolated in an area of diabase. The strike of the flows, as shown by the ridges, ranges from east-west to nearly northeast, with dips of 8° to 10° south. In Section 36 a large porphyritic flow forms a prominent homoclinal ridge occupying fully a third of that section. This flow is practically identical in character with that described in T. 55 N., R. 8 W.; they may have been connected, though the continuity is now broken by the large dike referred to above. North of Twin Lakes there is a long, narrow ridge of diabase, then an east-west valley which separates the ridge from a large, flat-topped hill of diabase occupying most of Section 24. This hill has a southwesterly projection which forms a homoclinal ridge. Excellent banding in the diabase strikes east-west and dips 15° south. Similar banding is found along the south side of the steep bluff that bounds the main hill. The strike there too is east-west with a 20° dip to the south. On the northwest side is exposed an amygdaloidal basalt hornfels with a strike northeast and a dip of 25° southeast. These data indicate that this large mass of diabase is essentially a sill. Dikes seem fairly common in this area. At the northwest side of this hill a dike of diabase cuts in a northeast direction through the flows which are overlain by the sill.

Another narrow ridge of diabase, probably a dike, containing a series of anorthosite masses, trends somewhat north of west from about the same point at which the above-mentioned dike ridge joins the main mass. Another small dike, cutting flows, forms a small fall on the Beaver River near the center of Section 22. Only small exposures of diabase occur in

Section 15; their topographic forms suggest sills. Several have exposures of basalt hornfels on the north side.

North of the highway in Section 14 are several diabase hills with some anorthosite inclusions and schlieren. Much of this diabase has banded structure with a variety of attitudes. The strike is generally N. 20° W., but the dip ranges from 30° to nearly vertical. The south side of Lax Lake is bounded by diabase in disconnected cliffs, some rising behind others in a series of steps.

Although the area north of Lax Lake has only scattered rock exposures, it is significant that all but one are composed of diabase and the associated red granite. Anorthosite masses are lacking except in Section 1, where several inclusions from 2 to 10 feet across occur in a diabase knob 500 paces east of the northwest corner of the section. Near the west quarter corner are several similar masses; the anorthosite fragments are intruded by diabase with chilled contacts. Along the north side of Section 2 is a series of coarse, diabasic magnetite gabbro exposures, with red rock dikes and red pegmatitic facies cutting the gabbro. The rocks are similar to some facies of the Duluth gabbro lopolith. This sort of material occurs throughout Section 3 and in the northern half of Section 10. Magnetitic gabbro, coarse red granite, and intermediate rock are common and appear to be part of one large mass, doubtless a large sill. Near the southwest corner of Section 10 is an exposure of porphyritic rock, which grades to a fine-grained rock at the base of the cliff. This is apparently a flow and probably marks the approximate top of the large gabbro sill.

In Section 11 a high, bare hill consists of a fine- to medium-grained olivine diabase, which weathers easily. Along the south side of the southwest quarter of the section is a long, narrow diabase ridge which is probably a dike. A small white anorthosite mass occurs low on the southeast side.

The largest and most favorably located anorthosite occurrence in this township is the high hill in Sections 26 and 27. The exposed rock of this hill consists mainly of anorthosite, but between the masses there is considerable diabase. It is generally safe to infer that covered areas are largely diabase, which is less resistant to erosion than anorthosite. The largest anorthosite area occurs on the west side of the hill and is very pure. (See analysis 5, Table 4.) Around the edges the anorthosite shows much shattering, which is brought out on weathering. Other anorthosite masses in this assemblage are large, but most of them have blotches containing mafic minerals.

At the south quarter corner of Section 26 are several large masses of anorthosite. The highest and probably the largest mass is fairly pure feldspar except for local blotches. Diabase stringers about an inch wide cut the anorthosite, and a few rods to the southeast many small fragments and crystals of anorthosite occur in the diabase.

Along the east side of Section 26 is a series of anorthosite masses in diabase. The most southerly outcrop is about 50 by 100 feet across, spotted with mafic minerals, in a surface which strikes N. 55° W. and dips 32° NE. The spots are elongated in the plane of the dip of surface or structure. The other masses are somewhat similar, but some are purer feldspar and differ in coarseness of grain. Banding in the diabase indicates a low dip and sill structure for the mass as a whole. Just across the section line in Section 25 is an unusual type of anorthosite with ellipsoidal masses of 1 to 6 feet, composed of impure anorthosite in relatively pure material. The strike of the long axes of the ellipsoidal masses is east-west and the dip is 55° to the south.

In the southern part of Section 25 is an extensive series of anorthosite masses, extending also into Section 36. These are mostly impure and of several varieties. There is also a very large-scale breccia of anorthosite fragments in diabase between the larger anorthosite areas. To the northeast are several large masses, the largest about 270 feet wide and 300 feet long, and others from 100 to 260 feet long. Most of these are spotted with impurities.

Township 56 North, Range 7 West (Plate 2)

Locations.—The mapping in this area was done mainly by north-south traverses starting from Highway No. 61, for which an accurate location map was made available by the Minnesota Highway Department. Side roads were surveyed by plane table and stadia, and temporary marks were put on the forty lines from which traverses were run. The private road to Micmac Lake was also surveyed and Micmac, Tettegouche, and Nipissiquait lakes were outlined by use of the plane table and stadia. Where stakes or bearing trees were found, land corners are indicated on Plate 2 by circles.

Surface Features.—The shore of Lake Superior cuts diagonally across this township in an average direction N. 37° E. The map clearly shows that in general the coast is relatively straight, but in detail there are irregularities, in most places related to the kind of rock found there and to its structure. The most conspicuous feature of the coast is the Great Palisades, which resulted from the erosion of a thick sheet of porphyritic rhyolite. The Little Palisades, a short distance east of the mouth of the Baptism River, are also rhyolite. Both palisades are conspicuously jointed, so that wave erosion maintains vertical cliffs. (See Figure 3.) Elsewhere the coast is rocky but with low cliffs.

The township may be divided into several topographic areas. The southwestern area, Sections 29, 30, 31, and 32, is rough and hilly with large diabase outcrops and anorthosite inclusions. This is separated from a somewhat similar area in Sections 5, 6, 7, 8, 9, 17, and 18 by a rather large valley now occupied by a small intermittent stream. This valley is floored with glacial lake sediments, and rock exposures are few except near the shore of Lake Superior.

The Baptism River occupies a narrow valley; in common with most of the larger valleys of the north shore, this is at least as old as glacial time, having been occupied by the waters of Lake Duluth during the retreat of the last ice sheet. Red clay is abundant along the valley floor, and in Section 4 a road-cut near the highway bridge over the Baptism River shows excellent varved red clay with complex folding. (See Figure 8.) Northeast of the valley of the Baptism River the area for a mile alongshore slopes gently toward the lake, but is broken by frequent homoclinal ridges of basalt flows. In Sections 2 and 3 is a high ridge, part of a diabase sill which trends northeast across the area into T. 57 N., R. 7 W. Northwest of this ridge and parallel to it is an almost equally prominent ridge composed of a thick ophitic flow.

Geology. — Plate 2 shows the wide distribution of diabase and associated anorthosite masses in this township. Sections 31 and 32 have enormous outcrops, and nearly everywhere there is some enclosed anorthosite. The diabase is mainly coarse and mottled; but along the north and west sides of the escarpment in Section 31 it is finer grained, suggesting that the base of the sill is not far beneath the talus. In the southwest quarter of the southeast quarter a very dense rock contains amygdules, indicating a hornfels derived from a flow. It is noteworthy that the diabase and anorthosite of the Beaver Bay complex, probably continuous from about 20 miles southwest, here give way to surface flows with diabase in only relatively inconspicuous exposures. It is probable that the sill thins out here and becomes interfingered with the flows, but it may turn east into the lake.

A series of flows are exposed along the north side of Sections 31 and 32. Another broad diabase mass cropping out in Sections 29 and 30 is a continuation of the mass near Twin Lakes to the west. Considerable red granite occurs near the top of the diabase sill in the southeast part of Section 30. The southern part of Section 30 has a gentle slope to the southeast, coinciding in general with the dip of the sill at the few places observed. The northwestern part of the section is rugged and has very large exposures of diabase and anorthosite extending northward into Section 19, where banding strikes N. 45° E. and dips 40° SE. The diabase in Section 30 is generally coarse-grained, but is not mottled except at the southeast corner. This diabase ridge continues into Section 29, where it is relatively flat-topped. Coarsely mottled diabase is common over all of the southern portion of the mass in Section 29. A hundred paces southwest of the northeast corner the diabase has an irregular banded structure with a general east-west trend. Along Williams Creek, below the highway, diabase is exposed beneath red granite and intermediate rock. Along the shore of Lake Superior near the mouth of the creek a confusion of red rock and diabase has an intrusive contact with rhyolite. A similar complex of diabase and red granite occurs widely in the southwestern portion of Section 21, and the surface has a gentle slope to the south in the direction of dip of the formations.

Most of the north half of this township is a diabase with much anorthosite. The northwest portion is particularly rugged; its four lakes occupy a picturesque setting, surrounded as they are by high bluffs of diabase and anorthosite. This complex appears to connect with the more southerly diabase through Section 19, but the fairly wide valley filled with lake sediments somewhat masks the actual physical connection. It is fairly certain that the diabase in Sections 6, 7, and 18 is not all one intrusive mass. About 100 paces west of the center of Section 18 a small exposure of amygdaloidal breccia in a steep slope suggests two diabase sills. Near the center of the southwest quarter of Section 7 is a considerable area of amygdaloidal basalt more or less metamorphosed. Exposures along the Tettegouche road in the northwest quarter show good flow bands in diabase, striking somewhat east of north and dipping 15° to the east.

Section 6 has many large exposures of diabase with much anorthosite; other exposures of diabase near Nicado Lake have schlieren which look like hornfels, striking east-west and dipping 15° to 20° south. In the northern portion of Section 17 there is a small hill of basalt. These small exposures of basalt in large diabase hills may be included blocks, or possibly poorly exposed flows separating resistant diabase sills.

The very high hill in Section 17 has a west- and north-facing escarpment, and a gentle back slope suggests that a sill dominates the structure. At the northeast side of the largest mass of anorthosite the feldspar rock lies directly on red granite; this is an uncommon occurrence. Section 9 contains a number of high hills and ridges of diabase which mark the eastward continuation of the large masses just described. These rocks extend along the Baptism River into Sections 3 and 4, apparently in one great mass. In the north part of the mass joints dip about 4° to the south, but near the southwest corner of Section 3 they dip 20° northwest, with a strike N. 20° E., suggesting some folding. Northeast of the Baptism River a large ridge of red ophite trends in a northeasterly direction across Section 3 and the northwest corner of Section 2.

A brief study of the map shows that in this township the exposures of lava flows are most extensive along and near the shore, with the belt widening greatly at the valley of the Baptism River and northward. It is probable that the valley was cut there because the flows were easily eroded.

At Silver Bay in the southwest part of the township are exposed a series of basalt flows with amygdaloidal tops, striking roughly at right angles to the shore. This results in a serrate shore line; at least eight flows are recognizable in Silver Bay. Several more flows, one a thick felsite, are exposed to the northeast, on shore and on Felsite Island. The

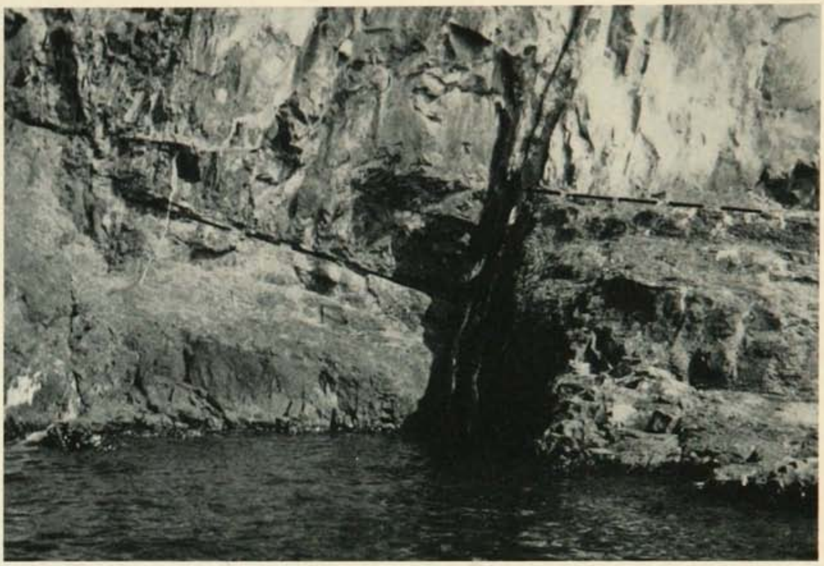


FIGURE 48. — Faulted top of flow, the Palisades, Lake Superior.

contact between basalt and felsite in the northeast quarter of the northeast quarter of Section 32 is a fault, described by Irving.[2] At the point northeast of Silver Bay eruptive breccia and tuff have well-developed block jointing. At the northeast corner of Section 32 flows strike parallel to the shore and dip 10° toward the lake. The felsite shows many complicated flow structures, and there is evidence of at least two flows.

The Great Palisades in Sections 21 and 22 form one of the prominent landmarks along the coast. Here the basalt flows are faulted (see Figure 48), are cut by dikes, and have an irregular dip, mostly to the southeast. Three may be recognized immediately below the large rhyolite flow. Just above the lower flow is a thin, cross-bedded sandstone. Bent pipe amygdules in the upper flows suggest that the lavas may, at least locally, have flowed east. Wave erosion has cut the cliffs to form natural archways beneath which it is possible to row a boat. The rhyolite exposures of the Great Palisades extend east to the southeast quarter of Section 15, where a diabase and granite dike strikes N. 70° W. and dips 80° NE. Northeast of that, basalt flows crop out as far as the point at the mouth of the Baptism River, where there is rhyolite.

There are probably three flows between the mouth of the Baptism River and the bridge at Highway No. 61. Above the bridge is a complex series of flows and intrusives. Twelve flows were recognized between the bridge and the north line of Section 15. At the big bend one-fourth mile

[2] R. D. Irving, *The Copper-bearing Rocks of Lake Superior* (U. S. Geological Survey, Monograph 5, 1883), pp. 310–11.

above the road is a high cliff of sedimentary rock, consisting of red conglomerate and shale, which strikes N. 70° W. and dips 10° S. In Section 10 eight additional basalt flows were recognized along the river; an extensive series of rhyolite and tuff outcrops occur from the high falls near the center of the section to a point near the north line. Above Kettle Falls in Section 3 are three more basalt flows. This increases the total between the lake and the diabase sill of Section 4 to at least twenty-six basic flows, in addition to some rhyolites.

Northeast of the Baptism River the rocks exposed alongshore and for over a mile inland are mainly flows. The most prominent exposure, and probably the thickest flow, is a rhyolite which forms the Little Palisades, a point about one-half mile northeast of the mouth of the river. (See Figure 3.) Probably eleven or twelve flows below the rhyolite strike N. 20° W. and dip 20°–30° E. The felsite extends to Crystal Bay and is also well exposed in cuts along Highway No. 61 at the junction with Highway No. 1.

Many thin flows are exposed along the shore in Section 1. At least fourteen may be counted between the diabase dike at the northeast corner of Section 11 and the dike about one-half mile to the northeast. These strike N. 80° W. and dip 65°–70° N. On the east line of Section 2 in the northeast quarter, the bluffs face east, several flows dipping west about 25°. The structure is evidently greatly disturbed from Silver Bay to the north line of this township.

The anorthosite masses of this township are extensive and complicated. Full description is impossible within the available space, but the details given below may be considered representative. The groups about Silver Bay are easily accessible and deserve special attention. They are notably abundant in the diabase west of the highway in Section 31. Most of them are impure, containing spots of ferromagnesian minerals. (See Figure 39.) There are many breccias of anorthosite fragments in diabase and other breccias of anorthosite with fine white feldspar matrix. The large masses in the southeast quarter of the northwest quarter were examined twice in a search for ceramic materials but were all so impure that they were not worth sampling. The large exposure in the northeast quarter of the southwest quarter of Section 32 seems to be comparatively free from ferromagnesian minerals.

On shore at the southwest corner of Section 32 is a series of anorthosite masses. One large mass contains crystals up to 6 inches in length, in a zone where most crystals are from ½ to 1 inch across. This particular mass of feldspar has coarse pyroxene segregations also. Intermediate between the feldspar and pyroxene masses are gradational facies. (See Table 4, analysis 9.) At the point on the south side of Silver Bay many angular fragments (xenoliths) of anorthosite occur in the diabase, and around the larger fragments the diabase is filled with small fragments (xenocrysts) of plagioclase. One large mass here has prominent bands which strike N. 80° E. and dip 16° N. At the point opposite the red granite island in the southeast quarter of Section 32 are several impure anorthosite masses cut by red rock in dikes and flat sill-like bands. The largest mass is almost pure feldspar.

In the northwest quarter of Section 30 are several large and many small anorthosite occurrences. The mass farthest south is rather pure and is surrounded by a breccia of anorthosite in diabase. Many of the anorthosite fragments are themselves brecciated and recemented by fine feldspar. Of other large masses in this occurrence some are coarse and pure and others fine-grained and impure.

At the center of Section 19 a great hump in the broad creek valley consists of very coarse anorthosite. Diabase is exposed on the northwest side and low on the south side, but not on the east. Viewed from the south, the mass as a whole and the joints seem to dip 6° or 8° to the east.

Sections 5, 6, 7, 8, 9, 17, and 18 of this township comprise perhaps the most extensive areas of anorthosite in the district. It is noteworthy that they seem to follow no law either as to size or distribution. About the only generalization that can be made is that they are associated with diabase.

The largest masses are in Section 17. It is possible that the particularly large exposure near the center is the largest of such masses in Minnesota. It consists of coarse, fairly pure feldspar. At one place on the northeast side, beneath a 100-foot cliff, the red granite underlies anorthosite with a horizontal contact; at another place the diabase anorthosite contact dips at an angle of 75° to the north. Another large mass a few rods to the northwest forms a north-facing cliff about 200 feet high. This mass is fully 500 feet across and seems to be entirely coarse, rather pure anorthosite. The many other masses in this section show much variety. Some are pure, and others of various degrees of impurity; some are very coarse-grained, and others are finer-grained than average. At places the exposure is a huge breccia with angular fragments of anorthosite in diabase. The diabase is in the main coarsely mottled.

The scattered masses in Section 18, those on the south shore of Micmac Lake in Section 8, and those in Section 7 show no unusual characteristics. At the northeast corner of Section 8 is a considerable anorthosite body with numerous basic spots.

Section 6 has numerous bodies of anorthosites southeast of the highway. The long hill of diabase with anorthosite inclusions in the southeast quarter of the section has been considered a classic example of the relation between the diabase and the feldspar masses. The anorthosite masses are irregular, angular inclusions in diabase (see Figure 32A), and occur especially at the top of the hill. The hill contains two kinds of diabase: a coarse facies low down on the hill contains a few anorthosite inclusions; and a fine-grained diabase intrudes and spreads above the first. The latter carries abundant anorthosite. The structure is sill-like with strike N. 20° E. and dip 25° SE. Possibly the diabase that carries the anorthosite in abundance is a later sill intruding the earlier one. (See Figure 32H.) The anorthosite ranges in size from minute fragments to masses several hundred feet long, such as that near the southeast corner of the section.

A belt from southwest to northeast across Section 9 contains numerous masses of anorthosite associated with diabase. Near the center of the southwest quarter is a high crest of coarse, light gray anorthosite. Along the north side of the section are several extensive occurrences; some very impure, with oval diabasic patches a foot or more across; others diabasic throughout; still others brecciated in diabase; and others still with zeolite between the feldspars. This belt in Section 9 continues into the southeast quarter of Section 4. The largest anorthosite here, 400 feet in length, lies in a direction N. 45° E. It is fairly pure but contains some spots of ferromagnesian minerals; at one place the spots are aligned in a direction N. 40° E. Northwest of the main mass are many smaller inclusions, some altered and some with coarse basic pegmatitic segregations at the contact with the diabase.

It is noteworthy that the large diabase ridge northeast of the Baptism River contains little anorthosite, whereas the ridges to the southwest contain a great deal. That the diabase belongs to the same series is borne out by its coarsely mottled character, similar to that of the diabase which usually carries the main anorthosite masses, and also by the occurrence in the southeast quarter of Section 3 of three good-sized and some smaller masses. The anorthosite consists mostly of a coarse and somewhat dark type of feldspar. The largest mass is 150 by 200 feet in extent.

The old Crystal Bay anorthosite quarry in the northwest quarter of Section 11 is a more or less isolated mass of anorthosite and diabase. Much of the anorthosite is notably impure with olivine spots. A series of good-sized masses also occur along Highway No. 61 in Section 1. This series is of a decided brown color. (See analysis 6, Table 4.)

Township 57 North, Range 8 West (Figure 49)

Locations.—Only a small portion of the eastern part of this township was examined. Points were located by pacing and by sun-dial traverse from known points in adjoining townships. A portion of Section 26 and all of Sections 25, 35, and 36 were mapped. (See Figure 49.)

Surface Features.—This area is typical of the rather level upland of the region. Rock hills and bluffs stand up above a low and often swampy general level. The hills are rounded masses of igneous rock which for the most part owe their forms to glacial erosion.

Geology.—The exposed rocks of the southeast corner of this township consist almost exclusively of intrusive igneous rocks and are part of an intrusive complex which forms a wide belt north of Lax Lake. This belt trends northeast to Finland and beyond.

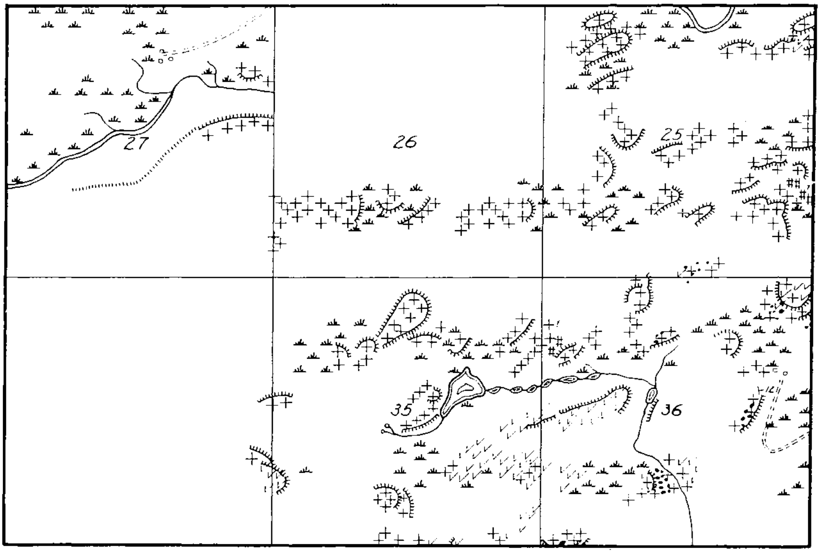


FIGURE 49. — Geologic map of a small portion of T. 57 N., R. 8 W.

In the southeastern portion of Section 35 and extending into Section 36 is an extensive series of red granite outcrops. In the western and northern portion of Section 35 there is a coarse diabase gabbro much like that observed in the area north of Lax Lake. Locally this basic rock becomes high in olivine and lacks augite, and may properly be called a troctolite. No anorthosite was observed in Section 35, but in Section 36 there are several occurrences, mainly in a finer-grained diabase than the diabase gabbro referred to above. Most of these anorthosite masses are fragments varying from a few inches to 25 feet across. Part of Section 36 has terminal moraine deposits covering the rock surface, probably to a considerable depth.

The exposures in Sections 25 and 26 are mainly coarse diabase gabbro, with a little red granite and some later dense basic dikes. The exposure in the southeast quarter of Section 25 mapped as a possible flow may be one of these later fine-grained intrusives, but its position beneath the gabbro suggests a flow rock.

Some reconnaissance mapping was done in Sections 1, 12, 13, and 14 along the east range line of the township. No exposures were found in Section 24, but several red rock outcrops were mapped in other sections, particularly along the Baptism River in Sections 1 and 12.

TOWNSHIP 57 NORTH, RANGE 7 WEST (PLATE 3)

Locations. — This township was mapped almost exclusively by sundial and pacing traverses along north-south lines at quarter-mile intervals, from known points on the old railroad grade and highway. All of the roads were surveyed by plane table and stadia rod, and the forty lines given temporary marks. A map of the Baptism River was obtained from the Finland camp of the Civilian Conservation Corps, under whose auspices the careful survey was made.

Surface Features. — Except for the southeast corner this township is part of the Laurentian upland, which extends from the north shore of Lake Superior to Hudson's Bay. The character is modified by the valley of the Baptism River, but the present river scarcely affects the topography more than half a mile on either side. The lower portion of the valley was flooded by the highest stage of Lake Duluth, which extended upstream to about the line between Sections 27 and 28. An excellent section of folded varved lake clay was noted in a road-cut just south of the highway bridge in Section 33. (See Figure 8.)

Above Section 33 the broad main valley and level areas drained by tributaries are floored with morainic material and outwash from the Superior Lobe. In Sections 5, 8, 22, and 23 are features of terminal moraine. Much of the soil is very stony, rock material having been scraped from the adjoining hills.

From the northeast corner of the township to Finland, the east branch of the Baptism River follows an earlier "strike valley"; this is determined by the easy erosion of some volcanics and by the greater resistance of the diabase sill, which has intermittent outcrops south of the river from Section 1 to Section 20. The main east tributary of the Baptism River also flows in a "strike valley" from Section 24 to Section 34.

The Baptism River, from Finland to its mouth, about six miles in a straight line, flows approximately across the strike, descending from an elevation of 1,340 at Finland to an elevation of 602 at Lake Superior. In this township it drops 300 feet.

Geology. — Rock exposures in this township are much less abundant than in most of the area of the anorthosite occurrences. Exposures are most numerous near the shore of Lake Superior, so that it was easy to obtain much detailed information on the bedrock geology. The map suggests that there are three belts of diabase with the general structure of sills striking diagonally across the township from southwest to northeast in line with the regional strike. At the extreme eastern edge of the township and extending into the next township east is a major diabase-anorthosite complex which must be essentially a dike, although it is probably very irregular.

The broad ridge of diabase in the southeast corner is continuous with the ridge described for the township to the south. The diabase in the southeast corner of Section 34 has a banded troctolite facies that strikes N. 10° E. and dips 20° E. In the southeast corner of Section 34 and southwest quarter of Section 35 the diabase is particularly full of anorthosite fragments.

In the southeast part of Section 26, on the north side of the ridge, the diabase has well-defined flow layers, which strike N. 30° E. and dip 10° SE. At the southeast corner of the section is a troctolite facies of the diabase, with flow layers that have a dip and strike similar to that just noted. This facies was traced to the northeast across Section 25. Along the southeast side of the ridge the structure strikes N. 45° W. and dips 10°–40° NE. A little northeast the strike is east-west with a dip of 10° N. Small exposures of diabase and several anorthosite hills mark the continuation of the sill in Section 24.

A few exposures of diabase near the center of Section 23 suggest a small sill in that area, but if it is there, it is largely covered by glacial drift. The diabase is much jointed in large, rectangular blocks, some rudely columnar. Some persistent joints dip gently southeastward.

Scattered outcrops of diabase in Sections 30 and 31 indicate an intrusive with a general trend to the north. In Section 30 the diabase is mixed with intermediate rock and red granite. Two exposures in Section 20 near Finland consist of troctolite with bands in various attitudes. Other scattered exposures indicate a diabase intrusive from the northeast quarter of Section 20 northeastward to the more numerous exposures along the line between Sections 10 and 15. This is a series of somewhat flat-topped, butte-like diabase hills of fairly coarse diabase with conspicuous jointing of a large, rudely columnar type. Rough columnar masses 30 to 70 feet high were observed dipping steeply to the northwest, suggesting an orientation at right angles to the plane of a sill. In the southeast quarter of Section 10 banding in a troctolite facies of the diabase dips gently to the southeast.

In the southwest quarter of Section 11 a prominent knob of diabase has a steep cliff facing northwest with flat joint surfaces striking N. 30° E. and dipping 9° SE. The diabase is very coarse and porphyritic, with phenocrysts of feldspar up to 1½ inches long. The porphyritic facies passes downward into coarsely mottled diabase. In this same quarter of Section 11, near the center line, there is a feldspathic diabase sill in basalt. This grades from coarse diabase downward through a rock with feldspar crystals ½ inch long to coarser material with feldspar crystals 3 inches long. This sill is unusual in having the feldspar concentrated at its base.

In Section 12 the monoclinal ridge with northwest-facing escarpment is continuous, and exposures are excellent. The rock consists mainly of coarsely mottled diabase with masses of anorthosite, which are described below. On the bluff south of the small lake the diabase is coarse, very basic, and has more magnetite than the normal diabase.

A connection between this sill area and the one to the south along the line between R. 6 and 7 W. is indicated by an unusual series of remarkable anorthosite and diabase exposures in Sections 12 and 13 of this township and 7 and 18 of the township to the east. That this connection is essentially dike-like in form can scarcely be doubted, as its trend is diagonal to the regional structure of both flows and sills. The surface continuity of this dike with the belt of intrusives to the south is broken by a preglacial stream valley in the southern part of Sections 13 and 18.

Beginning along the north line of Section 19 and trending northeast to Egge Lake in Section 4 is a complex of red granite and diabase. In Sections 18 and 19 the exposures are confined to the valley of the south branch of the Baptism River, and consist entirely of red granite. The hill north of Finland in Section 17 consists of reddish diabase and granite; along the top is a dike of fine-grained diabase with anorthosite. In Section 8 the diabase has locally traces of red feldspar, at some places such an abundance that it grades to red pegmatite. In the southwest quarter of Section 9 the diabase has little granite with it, but both diabase and granite occur to the north along the road.

Section 4 is a complex of red granite and diabase with the contacts commonly covered by morainic material. The southwest quarter of the section is largely red granite, but the east half has much diabase. The contact between granite on the northwest and diabase on the southeast is marked by a shallow gorge, at places only 20 or 30 paces wide, but the actual contact is not exposed. It is probably nearly vertical. Other exposures of red granite occur in Sections 5 and 6.

With the exception of the area along Lake Superior and one conspicuous ridge in Sections 24, 26, and 34, most of the flows of this township either occur as small outcrops along streams or are incidental to larger diabase masses. Because the flows are less resistant than diabase, it is inferred that much of the low area is underlain by flows, but this is by no means universally true.

Basalt flows are abundantly exposed along and near shore in Section 36. Banding and flow layers indicate a variety of structure. At the headlands of the bay the strike is northeast with a 10° dip to the southeast. Immediately back of the bay north of the road the strike is N. 15° W. and the dip 20° W. Near the north section line, the strike is again nearly parallel to the shore.

Extending along the northwest side of the diabase ridge from Section 34 to Section 24 is a fine, red, mottled or ophitic flow of considerable thickness and a distinctive character. The trend corresponds to the regional northeast strike and normally has a northwest-facing escarpment and gentle back slope to the southeast. The back slope, however, has also been eroded to form a cliff.

Along the Baptism River in Section 28 are several exposures of flows. Near the east section line and also one-fourth mile west are felsite flows with basalt. Near the east-west center line of the section the river falls over basalt flows. Above is a basalt tuff and breccia with a felsite overlying a rude dome in the basalt flow. More breccia is exposed along the river to the northwest.

Basalt is extensively exposed along the river in the south half of Section 20. This appears to be a single thick flow.

In the valley of the Baptism River between Sections 1 and 9 are several exposures of flows. These are basalt, some amygdaloidal and many considerably weathered except in the creek beds or gorges. The strike is nearly east-west and the dip 10° to the south.

The anorthosite masses of this township are mainly confined to three principal belts of diabase: (1) the area from Section 34 northeast to Section 24; (2) the big sill complex from Section 16 northeast to Section 1; and (3) the zone which more or less connects these two belts along the east side of the township in Sections 12 and 13. It is noteworthy that the complex of diabase and red granite along the west and north sides of the township contains very little anorthosite at any place.

The generally erratic distribution of anorthosite in the enclosing diabase is well shown by the occurrence in the southeast portion of the township. Around the lake in Sections 34 and 35 anorthosite is very abundant, but there is an area in Sections 25 and 26 where it is practically absent. Again large masses occur in the northern portion of Section 25 and the southern half of Section 24.

The exposure of anorthosite near the southeast corner of Section 34 appears to be one large mass, although it is partly covered at places. The south bluff is almost continuous, and no diabase is exposed, but anorthosite at the north end rests on diabase, suggesting a large sill-like mass dipping 10° east. The anorthosite has numerous small olivine spots.

The anorthosite hill on the west side of the small lake in Section 35 is also a large mass. This and the two masses east of the lake lie above diabase in the bluffs. There is a little olivine, giving a foliation with a north-south strike and vertical attitude. Near the center of Section 35 is a series of anorthosite masses varying from rather fine-grained white to coarse gray. The diabase is full of fragments of anorthosite, at places making up perhaps 50 per cent of the total.

Section 26, as previously noted, has little anorthosite, but along the south bluff in the southeast quarter is an occurrence with xenocrysts (or phenocrysts) and a single mass 6 feet across. There is also an inclusion of basalt 30 feet across.

South of the center of Section 24 is a high knob which shows nothing but anorthosite; however, it is only partially exposed at the top. The bluff is 100 feet high on three sides and all anorthosite. It consists of pale brown feldspar. Both to the north and to the south are other fairly large masses.

The occurrence in Sections 12 and 13 is part of what is probably the most extensive series of anorthosites in the region; as shown on Plate 3, it extends widely into the township to the east. As already stated, this is believed to be an enormous dike extending between the two main complex sills to the north and south. The sills in general strike from N. 35°

E. to N. 45° E., whereas the general strike of this dike-like mass of diabase and anorthosite is north-south at the south end; to the north it swings off to the regional northeast strike. On the west side this ridge has cliffs and bluffs fully 200 feet high. Some cliffs of anorthosite are estimated to be vertical for nearly 200 feet. In the northeast quarter of Section 13 a deep gorge cuts through the ridge, exposing metamorphosed amygdaloidal basalt below the diabase and anorthosite. The anorthosite ranges from small fragments or crystals to masses hundreds of feet in length and breadth. The character of the material also varies from a very pure, clear type to a coarse, dark type with inclusions of ferromagnesian minerals.

The anorthosite masses which occur in the sill south of the Baptism River are not as extensive as those just described, but they are typical and show many interesting features. Near the southeast corner of Section 1 is an anorthosite mass which extends as a ridge to the east. Several masses occur in this section. Viewed from the west, the anorthosite seems to occur only at the top of the diabase mass, for 100 feet of diabase are exposed beneath the lowest anorthosite.

In the southwest quarter of the northwest quarter of Section 12 the top of the knob is practically pure anorthosite, which locally shows much brecciation. Lower down on the bluff are many small fragments of anorthosite in diabase. The lower portion of the cliff is mainly diabase, but anorthosite fragments do occur down to the talus. Blocks of various sizes and shapes occur on this cliff. To the north are other large exposures of anorthosite in the diabase.

In Sections 11 a few masses of anorthosite are exposed along the top of the ridge. In Section 10, near the south quarter corner, are a few angular masses of anorthosite in a troctolite facies of the diabase.

Township 57 North, Range 6 West (Plate 3)

Locations. — This township was surveyed mainly by traverses running north and south at quarter-mile intervals from Highway No. 61, where the forty lines were located by chaining from known points. A plane-table survey was made of the road extending inland from Little Marais. Some of the sections in the northwest corner were mapped by traverses from the Finland-Cramer road.

Surface Features. — This township is rather simple physiographically, the greater portion being underlain by basalt lava flows that have been eroded to gentle slopes. The northwest corner has some extensive diabase-anorthosite ridges with the anorthosites projecting above the diabase as rounded crests. The shore line of Lake Superior is comparatively straight, approximately along the strike of the flows. Throughout the area the prevailing physiographic form is the homoclinal ridge trending northeasterly. The escarpment faces northwest, and the back slopes often coincide with the dip of the flows and sills.

The diabase of the northwest portion of the township has been deeply dissected by preglacial or interglacial erosion, and steep cliffs overlook flat, swampy valleys which have been partly filled with glacial sediments.

The Manitou River flows through the eastern portion of the township to join Lake Superior in Section 11. A few hundred feet above Highway No. 61 the river plunges over the Manitou Falls, one of the most beautiful along the north shore. The falls are not visible from the road, as there is a sharp bend in the river, but they may be reached by a trail along the east bank. The river makes a right-angle turn and plunges over a massive basalt flow to fall nearly 100 feet. At the base is a thick amygdaloidal bed, which the stream is undercutting, thus maintaining the falls. The migration of the falls has left a deep, narrow canyon, which is crossed by the highway bridge. Between the bridge and lake, a distance of scarcely half a mile, three more falls with a series of rapids give a total drop of several hundred feet. The last fall plunges the water directly into a small cove of Lake Superior. Above Manitou Falls the river flows in a relatively shallow valley, at several places over a bouldery bed. Locally it cuts through flows and forms a series of rapids.

One of the more striking spots along the shore is in Sections 10 and 15, where a thick basalt flow shows columnar jointing (see Figure 11) and solutions diffusing from the joints have produced peculiar diffusion bands or rings over the surface cleaned off by the waves (see Figure 12).

Geology.—In this township the trend of the diabase intrusives carries them inland. Section 6 has especially abundant exposures of diabase of somewhat varied character. In the northwest portion the rock is coarse and mottled, but farther south it is fine-grained. Just east of the center of the section is a weathered diabase with rhombic joints. In the northeast quarter a small amount of red granite occurs along the top of a diabase ridge, with joints striking east-west and dipping 20° to the south. This suggests that the slope is at or near the top of a sill. The sill is apparently continuous across the northwest corner of Section 5, where the diabase contains aplite stringers. A high, broad-topped hill of very coarse diabase extends through the east half of Section 5 and across the northeast portion of Section 4. In the southwest corner of Section 4 the surface of coarse feldspathic diabase strikes N. 33° E. and dips 12° SE. Considerable coarsely mottled diabase also occurs in the north part of Section 5; no anorthosite was observed, although it is commonly associated with this kind of diabase. The slopes suggest the dip of a sill. The diabase weathers into characteristic spheroids, the large ophitic patches being more resistant than the darker matrix.

For some distance along the shore in the southwest part of the township is a vertical cliff formed by undercutting of the amygdaloidal top of a basalt flow, two flows being exposed above. The strike is N. 30° E. and the dip is 10° SE.

A rhyolite flow extends into Section 30 from the section to the west.

Northwest of the highway in the southwest corner of Section 30 a thick amygdaloidal layer strikes N. 20° E. and dips 80° E., a very unusual attitude. On shore a tuff and breccia are exposed, and an abrupt contact, probably a fault, separates them from basalt of normal dip and strike. Similar tuff and breccia occur along the shore in the southeast quarter of Section 30 and may be the same bed repeated by faulting. Another exposure of tuff occurs a short distance south of the meander corner between Sections 29 and 30.

Many exposures of weathered flows occur in Section 20, but no unusual characteristics were noted. Just east of the Lakeside Inn in Section 21 an amygdaloidal bed strikes N. 70° E. and dips 25° SE. Its bent pipe amygdules suggest that the flow moved southeast.

Near the mouth of the creek in Section 21 pipe amygdules show an eastward flow, and the ropy surface of a lava flow is exposed. On shore east of the creek is the westernmost outcrop of the columnar basalt flow that extends nearly to the Manitou River. This flow forms a pronounced rocky ridge between the highway and the shore. It strikes about N. 35° E., and the dip ranges from 10° to 20° SE. In a small bay in the northeast quarter of Section 10 a red breccia is exposed, with columnar basalt on both points. Near the mouth of the Manitou River is a reddish, ropy basalt, probably the flow beneath the large columnar flow. Apparently this thick flow continues alongshore beyond the Manitou River to about the center line of Section 2, where a series of three flows and a breccia are exposed with a rather irregular contact. It seems possible that the large flow with columnar joints came in over the eroded surface of the earlier flows. Pork Bay, a rather pronounced indentation in an otherwise straight shore, is evidently filled with glacial material, as the rock surface is entirely buried. Northeast of the bay is a jointed flow which from its character may be correlated with the large columnar flow southwest.

Several exposures of lava flows occur along the Manitou River in Section 3. In the northwest quarter is a red shale, sandstone, and conglomerate bed resting on amygdaloidal basalt, with sandstone dikes extending into the amygdaloid. At the north line of Section 3 there is a rhyolite flow.

The anorthosites of this township are restricted to the northwest portion. The masses in Section 17 are worthy of note because they are the farthest east of any occurrence near shore in Lake County. No others are known between this and Carlton Peak, over fifteen miles northeast. This exposure consists of several masses, up to 30 feet across, of coarse gray anorthosite in a diabase matrix. A dike of diabase a foot wide cuts one of the larger masses and is literally filled with small fragments of anorthosite. Just to the west is the end of a ridge composed of a complex of diabase and anorthosite. Some of the anorthosite is fairly pure, other masses are full of spots and inclusions of ferromagnesian minerals. It is rather striking that the many exposures of diabase in Sections 4, 5, and 8 contain no anorthosite except in a single ridge near the northwest corner of Section 5, where hundreds of small blocks of anorthosite from 1 to 20 feet across occur in a fine-grained diabase.

The occurrences of anorthosite in Section 18 are continuous with those in T. 57 N., R. 7 W., and together form what is possibly the largest occurrence known, although the large mass on a hill south of Micmac Lake is much longer. Scattered anorthosite masses are found in diabase in the northeast portion of Section 18. Many of these seem to be very pure, light-colored feldspar, but others contain irregular spots and stringers of ferromagnesian minerals. In the southeast quarter of the northeast quarter is a complicated mixture of anorthosite, brecciated anorthosite, and diabase. Along the west line is such a profusion of anorthosite in diabase that only a rough representation can be made on the map. Some of the large masses seem very pure, but others show olivine patches. A deep gorge cuts through this mass, and extensive exposures occur on the slopes, indicating a considerable vertical scattering of the masses in the diabase. Exposures of diabase occur between the masses of anorthosite, but the greater part is covered by soil. It is usually safe to assume that much diabase occurs beneath the covered areas, as it is much less resistant to erosion and weathering than the anorthosite. This area extends into Section 7, but the greater number of anorthosite masses of the ridge lie in the township to the west, already described.

Along the south line of Section 6, and mainly in that section, is one of the most remarkable occurrences examined. In a narrow, somewhat broken east-west ridge over half a mile long, diabase appears locally at the base, but anorthosite appears down to the general level of the small amount of talus at the foot of the cliffs. Along the top the anorthosite is cut by diabase dikes, and small fragments of anorthosite occur in the diabase, which is dense at places, as if chilled by contact with the anorthosite. Some of the anorthosite is very pure and light-colored; some is dark gray. When viewed from a high point, the ridge is seen to have a series of rounded projections on the south side, as if scalloped in a huge way, the low points indicating diabase. This elongated mass of anorthosite probably occurs in a diabase dike, but the diabase has been largely removed by erosion or covered by surficial material.

Township 58 North, Range 7 West (Plate 4)

Locations. — The old north-shore highway runs near or along the south line of Sections 34, 35, and 36. This road is rarely used, but it was possible to drive along it in 1936 and a plane-table traverse was made. The forest road in Sections 28 and 33 was recently constructed by the foresters at Finland for fire protection. The camp workers also cut out a trail from Section 36 to Section 20, mostly along the abandoned Maple Branch logging railway spur. The forest road was surveyed by plane table, and points were located along the Maple trail by pacing. Because most of this area was beyond the anorthosite occurrences, traverses were made at half-mile intervals over much of the township instead of at the usual quarter-mile intervals. The rock exposures are therefore not mapped in as great detail as in most of the area covered by this bulletin.

Surface Features.—This township is rather typical of those portions of the Laurentian upland where the glacial deposits are not thick. The east branch of the Baptism River flows across the township, mainly as a sluggish, swampy, meandering stream broadening out to form Lake 23 in Section 23. At a few places the stream flows in a narrow gorge over rock outcrops, forming small falls and rapids.

In general the rock exposures form monoclinal ridges with north-facing escarpments and gentle back slopes to the south, but there are many exceptions. Aside from rock ridges there is rolling country, and probably glacial moraine on the high land, for example, between the lakes in Sections 31 and 32 and portions of 29 and 30. Where the area has not been burned, this high land supports much hardwood, particularly maple.

Geology.—Only a portion of this township was mapped. It is characterized by intrusive igneous rocks, but there are a few exposures of flows, some of them modified by contact metamorphism. The intrusives consist of a complex of diabase, troctolite, and red granite.

The western portion of the township contains few rock exposures. After this fact was established by traverses in Sections 20, 29, 30, 31, and 32, the mapping was not continued to the north and west. In general morainic deposits become so thick in that area that only a very high rock hill can reach the surface. Reconnaissance to the west and north in 1923 had also shown few exposures over a wide area.

In Section 33, particularly along the forest road, there are many exposures of a red granite with long hornblende crystals, at places forming a sort of lattice. Locally there is coarse basic gabbro. Near the northeast corner a north-facing bluff shows mostly basic rock below and intermediate rock above. Fluxion structure in the gabbro strikes N. 80° E. and dips 15° S. The intermediate rock transgresses the structure of the gabbro, but there is a transition zone of from 1 to 4 inches between gabbro and intermediate rock.

Eastward in Sections 34, 35, and 36 moraines are common. The few exposures consist mainly of normal diabase, but a felsite flow was noted near the road in the southern part of Section 35. To the north in Sections 25 and 26 the Baptism River cuts extensive red granite. Just west of the center of Section 26 a rock hill near the creek and old railroad grade shows a complex of troctolite, red granite, and brecciated, metamorphosed basalt. The troctolite has a vertical banding which strikes N. 15° E. About 250 paces south of the northwest corner is troctolite with small anorthosite inclusions. Banding near the northwest corner strikes east-west and dips 20° to the south.

In Section 27 are numerous exposures of troctolite in which the banding strikes roughly east-west and dips from 10° to 20° south. The same rocks and structures appear in Section 28, but here there is more variety in the attitude of the bands, and red granite is abundant. In the southeast forty along the road the diabase is gray, but has perhaps 2 per cent of red dikes up to 10 inches in width with fairly sharp contacts. South for some distance the red feldspar increases rapidly.

North of the Baptism River, from Section 20 eastward through Section 24, is a belt of troctolite exposures nearly a mile wide, comprising mainly one large sill but one of some complexity. The strike of flow bands is about east-west with dips generally 10°–20° to the south. The banding at places, particularly near the center of Section 20, is remarkable. About 400 paces south of the north quarter corner is a very coarse troctolite, irregularly mottled with coarse segregations or partly absorbed anorthosite patches. Most of the anorthosite is impure, but one boulder-like mass a foot across is pure white.

In Section 22 outcrops are very abundant, and the area was examined in detail. Most of the exposures consist of exceedingly well-banded, fine- to coarse-grained troctolite. (See Figures 24 and 25.) At places magnetite is more abundant than normal. In some zones the troctolite is very brown from the surface weathering of the abundant olivine. In the east half of the northeast quarter of the section is an extensive series of exposures of complex character. The most abundant rock is troctolite. About 200 paces south of the northeast corner is an exposure of basalt intruded by red rock. The basalt contains red feldspar phenocrysts and appears baked and dense. South of this exposure is a series with anorthosite masses in troctolite. These masses range from 15 feet across down to single crystals. Much anorthosite seems partly assimilated in the troctolite, which is very coarse. At places the troctolite is high in feldspar, suggesting rather complete assimilation of anorthosite. Some facies of the troctolite intrusive have an exceedingly coarse texture with segregated spots of great variety. Plastered against the face of the southernmost exposure is a pegmatitic intermediate rock with red feldspar.

Around Lake 23 are many large exposures of troctolite. Innumerable small anorthosite fragments occur in the troctolite, for example, 300 paces north of the southwest corner of Section 23. In Section 24 also there are numerous exposures of troctolite, as well as smaller exposures of red granite, normal diabase, and a basalt breccia.

In Sections 15 and 16 north of the big belt of troctolite there is an alternation of red granite and diabase, and a felsite occurs northwest of the small lake at the east quarter corner of Section 16.

Section 13 is a low, nearly level area with few outcrops; it is apparently covered by glacial outwash.

In the northeast quarter of Section 12 is a series of exposures of basalt flows and flow hornfels, with mottled diabase. An amygdaloidal basalt 200 paces north of the east quarter corner has a feldspathic gabbro inclusion 2 feet across.

The bluff 100 paces north of the east quarter corner of Section 1 is a complex of rocks. The north side of the ridge is diabase, but the south side is porphyritic diabase with plagioclase crystals up to 2 inches in length. It has inclusions of basalt, felsite, anorthosite, and gabbro.

Exposures, although abundant, are not complete enough to determine the structure of the intrusives in this area, but they seem to be sills. Whether there is one complicated intrusive or several is not certain, but the first possibility is the more likely.

Township 58 North, Range 6 West (Plate 4)

Locations. — The old north-shore highway enters this township from the south in Section 31 and leaves it to the east between Sections 1 and 12. A road follows an old railroad grade north from Cramer. These roads, as well as the farm road in Sections 10 and 15, were surveyed with plane table and stadia, and all forty lines temporarily marked so that traverses could be run either east-west or north-south, as convenient. The southeastern portion was reached from Highway No. 61, where forty lines were marked by measuring along the road surveyed by the Minnesota Highway Department.

The contour map of the Manitou River in the *Atlas of Water Resources of Minnesota,*[3] was of great help along the river. Some parts of the township are far from known locations; pacing and sun-dial traverses carried into these parts are naturally not as accurate as where more frequent checks are possible.

Surface Features. — The most prominent surface feature of this township is the broad, rugged diabase area which extends north and somewhat eastward from Sections 31, 32, and 33 to Section 3. The belt is practically three miles wide in the south half of the township, but northward narrows rapidly to a width of scarcely half a mile in Section 3. Topographically, this is an extremely complex belt. It evidently had a great effect on the course of preglacial erosion, as a valley, now partly filled, extended all along the west side, localized no doubt by the contact of the softer flows with the resistant diabase.

The present drainage has many peculiarities. The headwaters of the Baptism River, for example, extend to within about one-fourth mile of the main channel of the Manitou River in Section 20, and there is an imperceptible divide between the two drainage systems in the swamp along the line between Sections 20 and 29.

The Manitou River flows along the west side of the diabase ridge

[3] Report of the Water Resources Investigation of Minnesota, 1911–12 (State Drainage Commission and U. S. Geological Survey).

from beyond Section 3 to Section 20, where it turns and follows a narrow, youthful gorge across the ridge. The river is marked by a series of falls and rapids, the uppermost being near the southwest corner of Section 21. The gorge in the northwest quarter of Section 28 has a series of falls, and along the northwest side of the high anorthosite hill south of the center of Section 28 the river flows over a talus slope.

The profile of the Manitou River is steep from the upper falls in Section 21 to the south line of Section 28, then shows a rather gentle gradient to within one-fourth mile of its mouth, where it drops 225 feet to Lake Superior. The total drop from the falls in Section 21 to the mouth is 700 feet, nearly 300 feet being in Section 28.

In the southeast portion of Section 21 and the adjacent part of Section 22 is a particularly narrow canyon in diabase; the drainage now flows to the Manitou River at the west end, and to the Caribou River at the east end. This canyon was evidently eroded during an earlier erosion cycle than that which cut the present valleys of the Manitou and Caribou, which were certainly formed before the time of the Superior Lobe.

One of the striking geologic and physiographic features of the entire anorthosite area is the suddenness with which the diabase intrusive, and consequently the rugged topography, swings northward and disappears beneath a cover of glacial drift in T. 59 N., R. 6 W. In the region north of Beaver Bay there are three successive northeast-trending belts of diabase. These either gradually merge or die out, leaving in this township the one very prominent belt, which ends, so far as any eastward extensions are concerned, in Sections 15 and 22. The result of this situation is a very different type of topography in the eastern one-third of the township, drained by the Caribou River. This area is relatively level, with considerable swamp and a few low outcrops. Since most of the area was overflowed by Lake Duluth, the soils are mainly lake deposits. The Caribou River has cut rather deeply into this surficial deposit, exposing steep banks of gravel, particularly in Sections 11 and 14. This gravel must have been dumped into Lake Duluth by the contemporary Caribou River.

In its lower course the Caribou has a steeper gradient. Near the northwest corner of Section 25 it plunges over a basalt flow in a 35-foot falls. In Section 36, about half a mile above its mouth, it flows through a deep, narrow canyon in basalt flows and breccia and drops over two falls of 20 and 60 feet. A smaller pothole falls occurs below the highway bridge. The total fall of the river in about five miles, from the bridge on the road between Sections 2 and 11 to its mouth, is 600 feet.

The area northwest of the diabase ridges is somewhat level, with much swamp along the Manitou River and its tributaries. The topography is, in general, characteristic of the Laurentian upland. Gravelly and bouldery ridges between the swamps are glacial deposits. Level lowlands are mainly outwash, and there are marked terraces at places along the valleys.

Geology.—The most interesting geologic feature of this township is the intrusive complex which extends across the township from southwest to northeast. It is convenient to describe this belt beginning at the south.

Reference to the map (Plate 4) shows that in general the prominent belt of outcrop is bounded in the southern tier of sections by the Manitou River on the east and the headwaters of the Baptism on the west.

East of the east branch of the Baptism River in Section 31 is a high escarpment of coarsely mottled diabase, which, so far as observed, is free from anorthosite masses. The same coarse diabase is extensively exposed in Section 32. Along its east side anorthosites are common. In the southwest quarter, about 100 paces west of the south quarter corner, is an exposure of weathered reddish rock with red aplitic stringers, a sort of intermediate facies between diabase and red granite. To the north along the center line of Section 32 is a series of anorthosite exposures. The main enclosing rock is coarse diabase, but associated with the anorthosite are inclusions of dense amygdaloidal hornfels and rounded rhyolite porphyry. Basalt hornfels was also noted near the north quarter corner. These occurrences suggest that the diabase forms two or more intrusives, but possibly the other rocks may be large inclusions in one large diabase. In the northeast quarter of Section 32 anorthosite was observed in much finer-grained diabase than at most places. At many points in the diabase the structure suggests a sill.

In Section 33 there are fewer exposures, some coarse feldspathic, and some coarse olivinitic diabase. The diabase, so far as known, does not extend east of the river in Sections 33 and 34.

Section 29 has a complicated series of eroded masses of diabase. Most of the diabase is coarse, mottled, and olivinitic, but near the center of the section there is a peculiar reddish rock with segregations of acidic material and aplitic dikes and patches. Here, too, the absence of anorthosite is noteworthy.

Section 28 is crossed diagonally by the Manitou River, which exposes a rather good cross section of the rocks. In the southeast portion the river exposes rhyolite and rhyolite breccia. Rhyolite is also exposed along the river near the northwest corner. In the central part of the section the river cuts deeply into the diabase intrusive, exposing not only diabase but red granite and anorthosite. Much of the diabase is coarse and mottled. In the northeast quarter the diabase has inclusions of rhyolite porphyry and in certain zones coarse crystals of magnetite-ilmenite. There are also glistening cleavage faces of pyroxene up to 2 inches across.

A diabase ridge extends nearly across the south part of Section 27. The outline is dike-like in form, with flow banding, which is nearly vertical and trends east-west. The sides are finer-grained than the center. North of the center of Section 27 a somewhat similar belt strikes nearly north. This is probably also a dike, though it may merge with a sill to the north. These dikes probably represent the fingering out of the intrusive to the east, as no diabases are known in Sections 26 and 25.

Exposures of coarse diabase gabbro are abundant in the center of Section 20, principally along a monoclinal ridge with north-facing escarpment. Very coarsely mottled diabase also occurs on the nearly north-south ridges east of the road. No structures in the diabase reveal its form, but it is believed to be a much-dissected sill.

In Section 21 the diabase is decidedly variable, with very coarse to fine-grained facies. Much is olivine diabase or gabbro, and coarse diabase pegmatite is locally abundant. The eastern portion of the section is very high, with a general slope to the south, suggesting a sill.

The large ridge in the southern portion of Section 22 is mainly a medium-grained olivine diabase, which weathers to yellow and red; along the top it is coarser and contains magnetite and pegmatite segregations. The topographic form of this ridge, as well as its trend, suggests that it is a dike at the east end; vertical banding in the southwest quarter is confirmatory.

The isolated ridge in Section 23 consists mainly of coarsely mottled diabase. No structures were observed that would determine whether it is a dike or the remnant of a sill, but the form and trend suggest a dike.

In Sections 15 and 16 the diabase belt narrows greatly, and the exposures being very good, some definite observations may be made. The ridge which trends the length of Section 16 consists of a coarse olivine gabbro locally high in magnetite. In the northeast quarter rude, irregular vertical structures indicate that the mass is a dike. South of Kowalski Lake excellent banding strikes N. 30° E. and dips 15° SE., indicating a sill. This is mainly medium-grained olivine diabase, but differs somewhat from place to place. Near the center of Section 15 a rock spur projects eastward from the main ridge. This is composed of felsite and felsite porphyry with flow structure, and has characteristic closely spaced joints. This grades westward to a coarse rock, which is probably a result of recrystallization of some of the red flow by the diabase. There is no clean-cut contact, the felsite and coarser rock grading into each other.

In Section 9 it is noteworthy that the flows west of Cramer Lake strike at a sharp angle to the dike in the southeast portion of the section, proving the cross-cutting nature of the intrusive. In Section 10 the banding suggests a sill structure for a portion of the diabase east of Kowalski's road. The strike is about N. 45° E. and the dip 20° SE. North of the county road, however, the structure indicates a dike. For example, along the east bluff the flow bands are vertical and strike nearly north-south. In the middle of the mass, however, some bands are nearly horizontal. Evidently the structure of the intrusive is complicated.

In Section 3 the diabase zone is narrow, and the structure definitely indicates that the entire mass is a dike. The prevailing rock is a coarse diabase gabbro.

In Section 6 there are considerable areas of exposed rock, mainly intrusive, from troctolite to diabase. About 100 paces east of the center there are local inclusions of anorthosite and gabbro in diabase. Flow layers in the enclosing rock are vertical, suggesting a dike. Much of the troctolite near the center is light-colored on weathered surfaces and from a distance resembles anorthosite. These exposures are evidently part of an intrusive complex lying mainly north of those mapped for this report. Unfortunately, because most of the area is heavily drift-covered, not much can be learned regarding this complex.

West of the Baptism tributary is a considerable area in which scattered exposures are also mainly diabase. Review of the field data on Section 19 shows a continuation of the banded troctolite and red rock–diabase complex characteristic of the township to the west; there is more normal diabase in Sections 30 and 31. Considerable areas of morainic material conceal most of the rock of these sections.

Lava flows doubtless underlie much of the drift-covered area of this township, but only in the southeast corner, near Lake Superior, are exposures of these flows abundant. Alongshore near the mouth of the Caribou River the exposures seem to consist of one thick basalt flow. On shore at the county line two flows dip toward the lake and strike parallel to it, but small bays show a sort of arch in the flows. The upper flow has a number of red-brown clastic dikes, and the underlying amygdaloid is covered by a layer of red-brown, sandy shale of a character much like that of the dikes. Several flows are exposed along the Caribou River in Section 36; 500 paces north of the center of the section the river has two falls of 60 and 20 feet, respectively, formed by these rocks. The lower falls is the greater and probably marks a fault with hard flows on the north side and soft breccia on the south.

In the southeast portion of Section 2 is a long, northwest-facing escarpment of a gray, mottled basalt flow and a rather diagrammatic dip-slope to the southeast. Along the small creek in Section 35, a short distance north of Highway No. 61, is a red rhyolite flow which has such perfect banding that a thin section was required to determine that it was igneous and not a sedimentary rock.

A few scattered exposures of flows in Sections 11, 12, 13, and 14 show no unusual characteristics. It is worth noting that some exposures in Section 11 are rhyolite. Rhyolite flows are also well exposed along the Manitou River in Sections 28 and 33 and along the valley of the headwaters of the Baptism River in Section 31. The latter may be a large inclusion in the diabase complex of that area. Some of the flows near the south line of Section 17 have been baked to a hornfels by the intrusives. A red, mottled ophite flow is exposed at several places in Section 4.

The dike from Section 9 to Section 13 breaks the normal structure. Along its sides are exposures of flows dipping in various directions, probably locally disturbed by the dike. At no place in the township are exposures extensive enough to allow determining the regional strike of the surface flows and sills. Since the rocks north and south of this township trend northeast, the rocks here probably do the same.

The anorthosite masses are not as abundant in this township as in the townships to the southwest, except locally in Section 28. A few masses occur from one end of the diabase to the other. It is noteworthy that none was found along the west side of the main dike and sill. Their distribution is erratic, and no conclusions can safely be based on the lack of exposures in certain sections.

Small masses occur along the east side of the diabase belt in Section 32. Near the center of the section rhyolite inclusions occur with the anorthosite. In the northeast quarter is one fairly large anorthosite mass; and near it the diabase contains many small blocks of anorthosite and masses up to 30 feet in length. Much of the diabase in immediate contact with the anorthosite is finer-grained than the ridge as a whole; possibly the diabase carrying the anorthosite is a dike in the coarser diabase.

The high knob near the Manitou River south of the center of Section 28 contains several large masses of anorthosite. Northeast of the river is a belt or zone of occurrences trending northeast. The masses in this belt are of various kinds. The texture in particular ranges widely, from dense to coarse-grained. Some are gray in color, others have impure diabasic patches and rhyolite. Porphyry inclusions are also associated with the anorthosite. This belt continues into Sections 27 and 22, where two large masses of white, rather pure anorthosite form a high cliff facing east.

Two closely associated masses of anorthosite were found in the northwest quarter of the northeast quarter of Section 21. The larger mass is about 30 by 100 feet in surface exposure and occurs in a coarsely mottled diabase, whereas most of the rock of this section is a darker olivine diabase.

In Section 15 two good-sized anorthosite bodies occur in the ridge south of the Kowalski farm. To the southeast in Section 23 several masses occur on the northwest slope of a long diabase ridge. These consist of a very pure feldspar rock, and many xenocrysts and fragments occur in the diabase adjacent to the larger anorthosite masses, which are up to 30 feet across.

No anorthosite was found in Section 10; but in Section 3 there is a large hill which has been known for a long time, as it is a knob on a prominent ridge and can be seen from a distance, especially from the east. This mass is fully 500 feet long and about 400 feet wide, has nearly vertical sides, and stands nearly 100 feet above the adjacent diabase and talus. About 300 paces to the east there are several boulders of anorthosite up to 8 feet across embedded in diabase. The enclosing diabase near these has many light schlieren bands, which are irregular and so white with feldspar that they suggest anorthosite partly melted and smeared.

TOWNSHIP 59 NORTH, RANGE 6 WEST (PLATE 5)

Locations.—Locations in this township were determined by pacing and dial-compass traverses from the highway between Cramer and Wanless. The United States Forest Service from 1934 to 1936 worked over much of the township, marking the corners, meander corners, intersections of lines with roads, and railroads with yellow posters; these show locations enough so that the pacing was checked at many places.

Surface Features.—This area includes the headwaters of the Manitou River. In the northeast the streams flow east into Cook County. Two prominent ridges are noteworthy: one the northern end of the dike-like ridge that runs past Cramer, the other a dike trending northeast with few breaks from Moose Lake to Hare Lake. These ridges overlook wide, swampy valleys. Other ridges are less persistent. On the south side of Section 32 a considerable stream draining the western part of the township flows along a flat-bottomed valley in a peculiar braided pattern; near the southeast corner this divides into two streams, one flowing east, the other southwest, both ultimately to the Manitou River.

Both east and west of these ridges the outcrops are less numerous, glacial moraines concealing most of the rocks and dominating the topography. In the east row of sections outcrops are very few. Just north of the township is a remarkably fine esker which winds over hills and valleys for several miles. It is because of the common drift cover on each side, rather than because of any prominent bodies of anorthosite, that this township was added to the area mapped in this report. Nowhere else was it likely that the exposures would be sufficient to map a zone from the upper flows on Lake Superior to the great gabbro mass to the north. For twenty miles west outcrops are very scarce. Even in the township south of this, exposures are so few that such structures as dips and strikes are not well known.

Geology.—The general strike of formations through this township is about N. 55° E. This is roughly the trend of the lava flows and of the intrusive sills, but the general trend is transgressed by some large dikes. About two miles north of the northwest corner of the township lies the larger intrusive Duluth gabbro complex, its upper facies here a red granite ridge about a mile wide, with the same trend.

The general trend just mentioned results from the outcrop of beds and flows along the northwest side of the great syncline of Lake Superior, but the general dip toward the lake is not uniform in this area. In the northwest, Sections 5 and 6, the expected dip of 10°–15° SE. is indicated by contacts and by internal foliation in rhyolites and diabases; but a belt of diabase gabbro outcrops through Sections 9, 4, and 3. Section 2 has a foliation that dips northwest at low angles or is nearly horizontal. This gabbro is not separated by outcrops of other rocks from the gabbro along the railway in Sections 5 and 7, where it dips southeast; so the gabbro itself is probably a sill with a synclinal structure. Its wide area and resemblance to the Duluth gabbro make it probable that the belt of abundant outcrops continues far to the northeast in other townships.

Other diabases outcrop widely in the township as more isolated hills, for example, in Sections 10, 11, 13, 14, 15, 16, 27, 28, 31, 32, 33, and 34. Some of these may be high parts of connected masses of diabase, but outcrops are so few that the connections are not clear. The prominent dikes of diabase which can be traced for some distance deserve more detailed description.

The dike northeast of Cramer enters this township in Section 34, as a prominent ridge with bluffs on both sides. Outcrops and the topography indicate that it is continuous north to Echo Lake in Section 23, where the ridge flattens down and other dikes or sills join it from the west and southwest. Possibly the diabase hill near the quarter corner of Sections 27 and 34 is another branch dike from the southwest.

Two diabase ridges separated by a flat-bottomed valley run northeast through Section 21; at least the ridge southeast of the creek is dikelike in structure, with well-exposed vertical foliation. The diabase in Section 29 seems to be continuous with this dike, but the ridge turns more nearly south. Between this and the diabase peak near the center of Section 32 there are outcrops of rhyolite along a saddle in the ridge.

On the west side of Section 16 many boulders of porphyry suggest that at least one intrusive diabase in that area has feldspar phenocrysts. An outcrop south of the center of Section 9 is possibly related.

The surface volcanics exposed in the township are chiefly rhyolite and basalt flows, but along the old railroad grade south of the center of Section 32 is a low cut in coarse, fragmental rock — breccia or conglomerate — with a variety of boulders. The rhyolites show flow banding with crumpled complex structures, which give only a rough indication of the larger structures.

The basalt and rhyolite are not only mixed by explosive volcanic eruption (and possibly sedimentation), but have been a good deal affected by the later diabase intrusives. Contact action by the larger dikes and sills has made hornfels of the flows and brecciated and cemented some in confusion. The well-exposed contacts in Section 34 probably give very little evidence as to structures a few hundred feet away from the dike. The hill in the northeast quarter of Section 17 is probably surface rock altered almost beyond recognition. The rhyolite north of the center of Section 32 seems to enclose fragments of amygdaloidal basalt; the distortion suggests they were half melted,[4] but possibly some of the effect is a result of later diabases intruded near by.

The flows in Sections 3, 6, 11, 12, 13, 21, 27, 28, and 33 are poorly exposed. The large hill south of the center of Section 14 has felsite exposures with a reddish color and a texture so much like that on the road

[4] C. N. Fenner, "Some Magmatic Problems," *Journal Washington Academy of Sciences*, 24:113–24 (1934).

between Sections 12 and 13 that the trend of a flow is strongly indicated. The medium-sized outcrops of basalt in Section 31 and of rhyolite along the creek in Section 32 give no good indication of structure.

Anorthosite is not abundant in the exposures of this township. One knob nearly 200 feet long forms the crest of a hill in Section 32. It weathers white, but has perhaps 1 per cent of dark minerals. Diabase is exposed on the lower slopes of the hill on all sides, and on the northwest side the contact may be seen dipping southeast, indicating that diabase underlies the anorthosite at least part if not all of the way.

In the hill near the road in the southeast quarter of the southeast quarter of Section 28, diabase is thickly scattered with small blocks of gabbro and anorthosite, up to a foot or two across. Part of the matrix is fine and looks amygdaloidal, but close study indicates that the apparent amygdules are replacements, not cavity-fillings.

The only other anorthosite masses discovered in the township are in Section 21 along the dike ridges. Near the center of the section the bluff facing northwest has several large boulders of anorthosite, but more in the talus than in the diabase matrix. Much of the cliff looks white from the opposite side of the valley, but is an anorthosite gabbro facies of the dike. About a quarter of a mile north of the center of the section, on the west side of a narrow gap in the ridge, the diabase has a bouldery mass of a gabbro anorthosite, perhaps 50 feet across, with grains about ½ inch in diameter. Black augite makes up a little more than 10 per cent of it.

INDEX