UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY • BULLETIN 24
WILLIAM H. EMMONS, DIRECTOR

THE GEOLOGY OF THE ROVE FORMATION AND ASSOCIATED INTRUSIVES IN NORTHEASTERN MINNESOTA

BY
FRANK F. GROUT
AND
GEORGE M. SCHWARTZ

MINNEAPOLIS • 1933
THE UNIVERSITY OF MINNESOTA PRESS

AUTHORS' PREFACE

In the large area of Rove formation along the boundary of northeastern Minnesota and Ontario there have been two important silver mines, both on the Ontario side of the boundary—Silver Islet and Silver Mountain. The existence of a number of smaller mines and prospects makes it certain that mineralization of this kind occurred over a wide area, and several other mineral occurrences have long been known; but no other important deposits have been developed. Since much of the area is concealed under glacial deposits and since only a reconnaissance geological survey had been made in the part of the area that lies in Minnesota, it seemed advisable to survey the area in more detail. An effort was made to map and study all large outcrops and most of the smaller ones, to record where the veins are and what is their nature, to map the formations more closely than before, and on these records to base an estimate of the probable mineral prospects of the district. The Gunflint iron-bearing formation, which has been treated before,[1] is here referred to only incidentally.

The Minnesota area of Rove slate is a narrow strip south of the international boundary from Pigeon Point to a few miles west of Gunflint Lake in Cook County. (See Figure 1.) Since the base of the formation trends northeast into Ontario and the beds dip south, it is believed that eastern outcrops in Minnesota are at a higher horizon than those near Gunflint Lake.

The district was, until recently, reached as a rule by taking boats on Lake Superior or trains to the Vermilion Range, then, in either case, going the rest of the way by canoe, the length of the trip depending on the part of the belt visited. From Port Arthur, Ontario, the Port Arthur, Duluth, and Western Railway once ran trains to Gunflint Lake, but the rails have been removed west of North Lake Station, and trains do not run regularly even that far. State Highway No. 1 was improved in 1917 and connected from Grand Marais to Port Arthur through the Rove area. The first automobile passed over the bridge across the Pigeon River on April 27, 1917, and the formal opening and general celebration took place on August 18, 1917. In 1925 and 1926 a road was improved that connected the new State Highway No. 1 at Grand Marais with Gunflint Lake. Other roads are uuder construction, and it seems probable that the lakes of the area will be visited much more often than heretofore. Its increased accessibility is an added reason for acquiring information about the geology and mineral prospects of the area.

[1] T. M. Broderick, "Economic Geology and Stratigraphy of the Gunflint Iron District, Minnesota," *Economic Geology*, 15:422–450 (1920); J. E. Gill, "Gunflint Iron-bearing Formation, Ontario," Summary Report of the Geological Survey of Canada, 1924, Part C.

The writers undertook the work on this area in 1925 and continued the field work in the seasons of 1926 and 1927. Field and office assistance has been rendered by Messrs. John W. Gruner, Don Davidson, F. A. Gray, Ronald Brown, T. F. Andrews, Elliott Griffith, F. G. Wells, Nathan Davies, William Pettijohn, and LeRoy Hassenstab. Mr. M. S. Green of Mineral Center and Mr. Eben Falconer of Susie Island have been especially helpful in supplying information as to mining prospects. Mr. Don Davidson and Mr. Hugh Kendall did some petrographic work

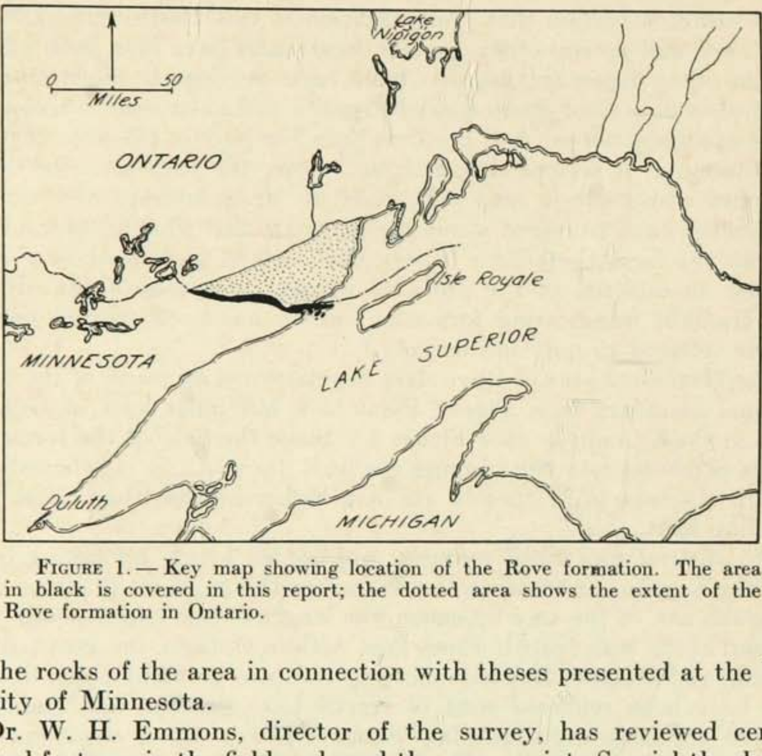


FIGURE 1. — Key map showing location of the Rove formation. The area in black is covered in this report; the dotted area shows the extent of the Rove formation in Ontario.

on the rocks of the area in connection with theses presented at the University of Minnesota.

Dr. W. H. Emmons, director of the survey, has reviewed certain critical features in the field and read the manuscript. Special thanks are due to him for valuable suggestions.

The area includes the route of some of the earliest travelers who reached Minnesota. The early travel from the region of the Great Lakes to Hudson Bay started over the nine miles of the Grand Portage, all of which is underlaid by Rove slate and its associated rocks. This was one of the busiest highways in the state from 1731 to 1804 and is mentioned in treaties with Great Britain.[2] Thousands of journeys to and from civilization, on which furs were taken away and supplies brought in, made the Grand Portage a strip of historic ground. With

[2] Solon J. Buck, "The Story of the Grand Portage," *Minnesota History Bulletin*, 5: 14–27 (1923).

the building of transcontinental railways both south and north of Lake Superior the Portage has rapidly fallen into decay and is now almost lost in the encroaching growth of underbrush. Parts of the trail were used by logging companies; but the site of Fort Charlotte at the northwest end was not on the road, and it is now hardly recognizable.

It is interesting to note that the Grand Portage owes its location to the topography of the region, which made any other routes to the interior canoe waters impractical.[3]

Previous work in the district has been reported by Winchell and Grant in the publications of the State Geological Survey.[4] Special studies have been made at Pigeon Point[5] because of its petrographic interest and at Susie Island and the Green homestead[6] because of prospects of ore.

The present study brings together all these studies and adds the topographic and geologic maps of the whole district on a better scale than previous maps. The beds are so thin, however, that even this scale does not suffice to show all the details that were seen in the field work.

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

University of Minnesota
March, 1933

[3] G. M. Schwartz, "The Topography and Geology of the Grand Portage," *Minnesota History,* 9:26–30 (1928).

[4] N. H. Winchell and others, *Final Report of the Minnesota Geological and Natural History Survey,* 4:313–345 (St. Paul, 1899).

[5] W. S. Bayley, *The Eruptive and Sedimentary Rocks of Pigeon Point, Minnesota* (United States Geological Survey Bulletin 109, 1893); R. A. Daly, "The Geology of Pigeon Point, Minnesota," *American Journal of Science,* 4th series, 43:423–448 (1917); and F. F. Grout, "Anorthosite and Granite as Differentiates of a Diabase Sill on Pigeon Point, Minnesota," *Bulletin of the Geological Society of America,* 39:555–678 (1928).

[6] G. M. Schwartz, "A Sulphide Diabase from Cook County, Minnesota," *Economic Geology,* 20:261–265 (1925), and "Copper Veins on Susie Island, Lake Superior," *Ibid.,* 23:762–772 (1928).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

GENERAL FEATURES OF THE REGION

The area underlaid by the Rove slate in Minnesota is still relatively unsettled and because of the rugged character of the topography will probably remain so except for lodges and cabins for summer homes.

The only village with a post office within the area is Grand Portage, which is still largely an Indian settlement. Lodges or private cabins are located on Gunflint, Loon, Hungry Jack, Clearwater, McFarland, and East and West Bearskin lakes. A hotel and a customs office are located

FIGURE 2. — Hungry Jack Lake, looking northwest. Typical of the long, narrow lakes of the Rove area.

at the Minnesota end of the International Bridge at the end of Minnesota Trunk Highway No. 1. A half dozen settlers and a few fishermen on Pigeon Point were the other inhabitants at the time the work was done. The post office of Mineral Center lies just south of the area in T. 63 N., R. 5 E.

Much of the area was originally covered with white pine forest, but most of this has now been cut or destroyed by fire. Part of the area from Pine Lake to Hungry Jack Lake is within the Superior National Forest. The remainder is under the care of the Minnesota Forest Service.

The drainage of the region is divided between North Lake and South Lake, one portion draining north into Hudson Bay and a larger portion draining east into Lake Superior and the St. Lawrence River. The courses of the streams are largely determined by the geologic structure, which is, in brief, a series of alternating hard and soft rocks dipping gently to the south. The deeply cut troughs between hard ridges hold a series of beautiful lakes (Figure 2), and the details of the streams now draining the troughs were probably much modified by glaciation. Transverse valleys are not numerous, but there are a few that have important effects on the drainage.

The relief is from 602 feet at Lake Superior to nearly 2,100 feet above sea level on the ridge north of Clearwater Lake. The sharpest high mountain is probably Mount Josephine, which rises from Lake Superior to 1,370 feet, between Grand Portage Bay and Wauswaugoning Bay.

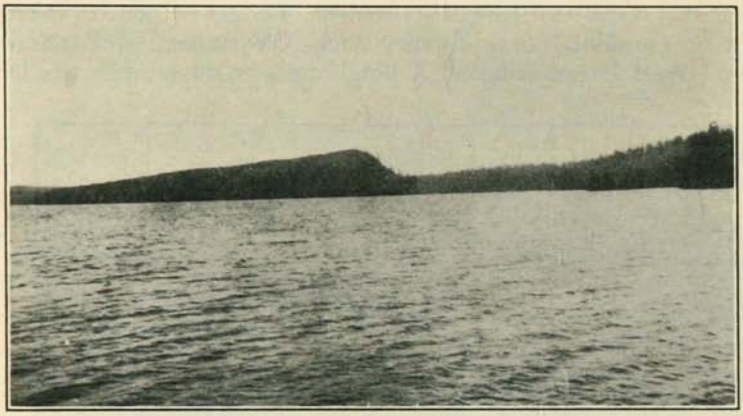


FIGURE 3. — Dip slope of diabase sill overlying slate. Looking west on Alder Lake, T. 61 N., R. 1 E.

A broad view of the district from the high peaks or in the transverse valleys shows gentle dips to the south and steep cliffs or talus slopes facing north. (See Figures 3 and 4.) The impression is that of a series of "saw-tooth mountains," which seem to be attributable to differential erosion,[1] though faults may add certain of the "teeth" to the general effect.[2] A few more isolated peaks are related to dikes or other hard rocks.

The general accord between the levels of the higher ridges and the accord between these and the great granite plateau to the north suggest a post-Keweenawan peneplanation. Certainly the structure of the district shows that erosion was profound. Since that peneplanation the summits have been preserved with only slight modification by weathering, stream-cutting, and glaciation; most of them still stand at 1,800 to 2,000 feet above sea level.[3]

No accurate map of the region underlaid by the Rove formation was available when the work was started. It was necessary to use the township plats of the General Land Office for a base. It was realized at once

[1] U. S. Grant, *Final Report of the Minnesota Geological and Natural History Survey*, 4:485 (1899).
[2] L. Martin, United States Geological Survey Monograph 52 (1911), p. 98–99.
[3] Frank Leverett, *Moraines and Shore Lines of the Lake Superior Region* (United States Geological Survey Professional Paper 154A. 1929).

that the slight dip of the rocks and the saw-tooth topography would give a distribution of the rocks that could be adequately understood only when combined with a contour map. The topography was accordingly sketched as the geologic work was done. North-south traverses were run each quarter of a mile. The elevations of the lakes had been rather carefully determined by the work of the earlier survey under N. H. Winchell, and these, with the accurate maps of the international boundary, were used as control. Small barometers were used for all

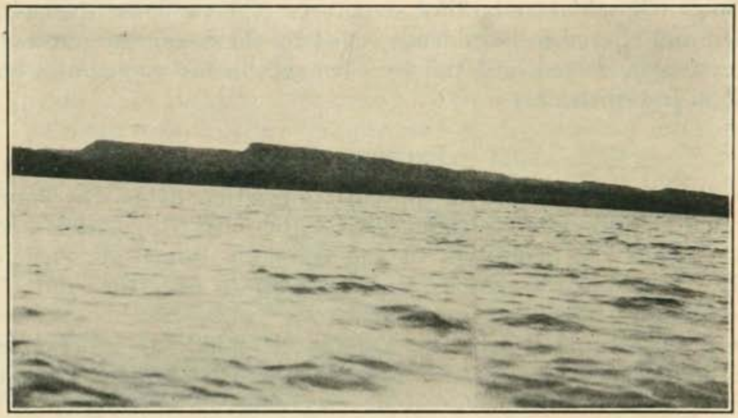


FIGURE 4. — "Saw-tooth" topography of diabase sills. North Lake, international boundary, looking east.

elevations between known points. The contours were sketched in the notebooks with a 20-foot interval. On the map accompanying this report an interval of 40 feet is used, as the 20-foot interval might imply too great accuracy in the mapping of the topography.

The rocks of the district are all pre-Cambrian except the Pleistocene and Recent deposits. The formations below the Animikie occur north of the area mapped.

TABLE OF FORMATIONS

Recent	Alluvium and beaches
Pleistocene	Drift and beaches
	(Great unconformity)
Keweenawan	Duluth gabbro
	(Intrusive contacts)
	Logan sills and dikes
	(Intrusive contacts)
	Basalt flows, breccias and tuffs
	Sandstone and conglomerate
Animikie	Rove formation
	Gunflint (iron-bearing) formation
	(Great unconformity)
Lower Huronian (or Archean)	Knife Lake slates
	(Great unconformity)
Archean (Laurentian)	Batholithic intrusives, mostly granite
	(Intrusive contacts)
Archean (Keewatin)	Ely greenstone

The Rove slate and Logan sills, which are the subject of this study, lie between the Gunflint iron formation at the base of the Animikie and the overlying flows and sediments of the Keweenawan. The Animikie series as a whole, however, is in contact at Gunflint Lake with a series of older rocks.

KEEWATIN

The Ely greenstone outcrops three miles to the west of the narrows between Gunflint Lake and Magnetic Bay. It is largely chlorite schist but shows ellipsoidal and other structures of lava flows. It has been intruded and altered to hornblende schist by the Saganaga granite. The formation is described in detail by Clements in his monograph on the Vermilion iron district.[4]

LAURENTIAN

The Saganaga batholith is the chief formation below the Animikie series near Gunflint and North lakes. It was eroded to a relief of perhaps 50 feet before the deposition of the Animikie formation. The early Animikie is highly ferruginous, and the granite near the contact has been strikingly stained by iron oxides.

The granite exposed near the Animikie is chiefly a border phase of the batholith, syenite, or diorite, rather than coarse granite with quartz "phenocrysts," such as is found on Saganaga Lake.[5] Much of it is gneissic. Dikes of similar composition cut the greenstone.

OTHER PRE-ANIMIKIE ROCKS

In places north of Gunflint Lake where there are exposures of iron-bearing rocks and limestone of the Animikie along the shore, there is a complex of several rock types between the shore and the granite crest of the ridge. Besides the greenstone there is a good deal of gray slate that closely resembles the Knife Lake slate found in large outcrops a few miles to the west. Its relations to the greenstone have not been determined, and the rocks are not exposed on the Minnesota side of the lake.

Intrusive into slate and greenstone are some silicic porphyry dikes and sills, somewhat schistose and carbonated. These might reasonably be considered apophyses from the granite, but this also is uncertain. The granite is known to be older than the Ogishke-Knife Lake series; so if the porphyry is contemporaneous with the granite, the slate is older than the Knife Lake. On the other hand, if the slate is Knife Lake, the porphyry is a silicic intrusive of later age than the granite. Detailed work is needed on the Canadian side to settle these problems of the basement complex.

[4] J. Morgan Clements, *The Vermilion Iron-bearing District of Minnesota* (United States Geological Survey Monograph 45, 1903), p. 130–169.

[5] F. F. Grout, "The Saganaga Granite of Minnesota-Ontario," *Journal of Geology*, 37:562–591 (1929).

The Animikie Series

With a distinct unconformity the later series overlie the rocks just described. The break is marked by a basal conglomerate in the overlying Gunflint iron-bearing rocks, by a change in dip from nearly vertical in the older rocks to nearly horizontal in the later, by a transgression of the later rocks on a whole series of different older rocks, by an absence in the younger rocks of such dikes of porphyry and granite as intrude the older rocks, and by less folding and metamorphism in the younger rocks than in the older. The later series in Minnesota are not separated by any such profound unconformities as that between the Knife Lake and Animikie series. The younger series in Minnesota have been commonly divided into the Animikie and the Keweenawan. In the adjacent area to the east, Tanton has divided the younger rocks into similar series; he finds a limestone series (Sibley) at Thunder Bay which does not reach into Minnesota.[6]

The iron formation.—The Gunflint iron-bearing member of the Animikie is 300 to 700 feet thick and rests upon the eroded complex with a minor amount of conglomerate at its base. This may be observed on the north shore of Gunflint Lake. The formation is divided into four members, like its better known equivalent, the Biwabik formation of the Mesabi Range.[7] Many prominent layers have a characteristic granule texture. Metamorphism has been more intense than in the main Mesabi district, and much of the iron oxide is magnetite. The upper beds contain a good deal of carbonate in comparison with the lower beds and the overlying slate.

The Gunflint formation extends east from its exposures on Gunflint and North lakes into Ontario in a direction about N. 70° E.[8]

The Rove formation.—The Rove formation rests conformably on the Gunflint iron-bearing rocks, but the contact is not well exposed, and both formations are intruded by a series of diabase sills. The Rove is about 1,500 feet thick in Minnesota, and it is more sandy in its upper parts than near the base. Above it is a Keweenawan sandy sediment with a dip so nearly the same as to leave doubt as to the presence of an unconformity, though the occurrence of a conglomerate suggests one. The conglomerate may be seen in T. 64 N., R. 4 E. (See Plate 11.) Since the formation has no secondary cleavage, it is properly an argillite rather than a truly metamorphic slate. The formation in Minnesota is described below, pages 11 to 35.

In the district northeast of Pigeon Point the Rove formation is described by Tanton,[9] and it appears to pinch out northeast of Thunder

[6] T. L. Tanton, "Stratigraphy of the Northern Sub-Province of the Lake Superior Region," *Bulletin of the Geological Society of America*, 38:731–748 (1926), and *Fort William and Port Arthur, and Thunder Cape Map Areas, Thunder Bay District, Ontario* (Memoir 167, Geological Survey of Canada, 1931).

[7] Broderick, *op. cit.*

[8] E. D. Ingall, "Mines and Mining on Lake Superior," Annual Report of the Geological and Natural History of Canada, 1889, p. 21H and map; Gill, *op. cit.*

[9] Tanton, *op. cit.*

Bay. Probably the considerable thickness exposed near Rove Lake indicates that it originally was still thicker farther southwest, perhaps continuous with the thick Virginia slate of the Mesabi Range. It is now interrupted, however, by the Duluth gabbro, so the continuity in that direction is only inferred. It has the same general character and the same stratigraphic position as the Virginia slate.

Keweenawan Series

The oldest rocks of this series seem to be sandstones and conglomerates lying above the Rove slate and below the early basaltic Keweenawan lavas. The contacts with the Rove slate are not well exposed. The Keweenawan sediments and flows are found only east of Pine Lake, as the Duluth gabbro has eliminated them to the west. In most places the base of the Keweenawan is at the foot of a bluff capped with lava flows. The sandstones and conglomerates crop out in the bluff, north of which is a swamp or concealed area, followed by outcrops of Rove slate. (See Plate 12, which shows an example from Sec. 3, T. 63 N., R. 5 E.) In one or two places the abundance of conglomerates suggests a basal phase of a younger series, and in one or two others the base of the Keweenawan bluff has outcrops that resemble the Rove rather than the beds above the conglomerates. The distinctions even in these outcrops are not very conclusive. Petrographically the upper part of the Rove approaches very closely the nature of the basal Keweenawan, including pebbly beds and sandstones with a peculiarly slabby parting. This uncertainty of the contact of Keweenawan and Animikie beds is very different from the marked unconformity of Keweenawan on the slates west of Duluth, but the relations are similar to those shown farther east in Ontario.[10] These supposedly Keweenawan sandstones are whiter, however, than the average Rove sandstones, except where the Rove is altered by gabbro. They are also much more cross-bedded and less firmly cemented than the Rove, and the grains are more rounded. On the basis of these features and the field relations they have been separated with some confidence in the mapping.

The Keweenawan sandstones attained a thickness of over 100 feet at some places before igneous flows covered them in this district. As is characteristic of the Keweenawan, they probably formed as continental rather than as marine sediments.[11] There is little sign that the sediments in the lower part of the Keweenawan carry fragments of Keweenawan igneous rocks.[12]

[10] Tanton, *Fort William and Port Arthur, and Thunder Cape Map Areas, Thunder Bay District, Ontario* (Memoir 167, Geological Survey of Canada, 1931). East of Thunder Bay the Rove formation is separated from the Keweenawan by a series of red shales and limestones not found in Minnesota, the "Sibley" series. Tanton names the basal Keweenawan sediments the Osler series.

[11] C. R. Van Hise and C. K. Leith, *The Geology of the Lake Superior Region* (United States Geological Survey Monograph 52, 1911), p. 366–427.

[12] Grant found rhyolite in the conglomerate on Grand Portage Island, but this does not prove that the basal sediments have rhyolite. The sediments on the island alternate

Thin sections show not only alkalic feldspar and quartz but also some chert and jasper sand grains and the common accessories zircon and apatite. There is considerable recrystallization of the cement to hornblende and chlorite.

The flows of the middle Keweenawan began in this district with basalts, which are amygdaloidal in their upper parts. Single flows range in thickness from a few feet to over 100 feet, much as do those at the same horizon near Duluth, and they accumulated to great thicknesses. Later eruptions included a great variety in composition. Even the early flows differed among themselves, especially in the kinds of amygdules. There were various phases — glassy, porphyritic, spherulitic, and diabasic. Most of the flows are now somewhat altered and green.

Most of the boundary between the Keweenawan and Huronian formations in the region under discussion had not been accurately located in previous maps of this region. It is shown in a general way on the map of Cook County in the Winchell report on the geology of Minnesota.[13] For the most part the present map shows the boundary somewhat farther north than the older map and thus reduces the area in Minnesota underlaid by the Rove formation. It is of interest that the contact is closely located as far east as the islands south of Pigeon Point, where Susie (Governor's) Island consists of slate and intrusives, and Lucille Island and Belle Rose Island are composed of Keweenawan flows. The earlier map shows the islands correctly, but on account of the small scale the legend was left the same for all.

The Logan sills (and dikes) intrude the Keweenawan flows and all older formations. (See Plate 12.) This age relation is based more on dikes than on sills; but dikes and sills are so related in the district that it is fairly safe to assume their correlation. Most of them are diabase, and the fresh similar diabase dikes cutting the granite north of Gunflint Lake are probably of the same age — possibly feeders for the sills in the sediments. Sills are abundant in both the Gunflint and the Rove formations and are named for Dr. William E. Logan, a Canadian geologist, who first described them.[14] The diabase intrusives are described in detail below, pages 36 to 59.

Intrusive into the older formations in the western part of the district is the Duluth gabbro lopolith. This portion of the great mass is a sill-like extension running east from the north side of the main mass along a horizon near the base of the Keweenawan. The end of this finger lies

with flows and with some igneous breccia. It is of course possible that some rhyolite was extruded as flows before any Keweenawan sedimentation took place, as suggested by Hotchkiss from a study in Wisconsin, but no such sequence is indicated here. U. S. Grant, in *American Geologist,* 13:437 (1894); W. O. Hotchkiss, "The Lake Superior Geosyncline," *Bulletin of the Geological Society of America,* 34:669–678 (1923).

[13] *Final Report of the Minnesota Geological and Natural History Survey,* Vol. 4, Plate 69.

[14] A. C. Lawson, *The Laccolithic Sills of the Northwest Coast of Lake Superior* (Minnesota Geological and Natural History Survey Bulletin 8, 1893), p. 48. N. H. Winchell, *Final Report of the Minnesota Geological and Natural History Survey,* 5:289, notes that

in the basalt flows, about Sec. 27, T. 64 N., R. 3 E. West of that the base of the gabbro is not strictly concordant with the structure (unless possibly following an unconformity), cutting down across the basal sediments of the Keweenawan and gradually across the Rove slate also, until west of Gunflint Lake it reaches into and through the iron-bearing rocks of the Animikie.

It is an olivine gabbro in most outcrops, but it is diabasic in many others, and in these it is indistinguishable in hand specimens from the central parts of some of the large Logan sills. It is, however, somewhat more variable and more generally banded, and it has associated as an upper phase a more silicic differentiate than most of the sills.

The relative ages of the gabbro and sills are shown clearly by the fact that some of the sills are recrystallized at the gabbro contacts. An instructive outcrop occurs south of Mayhew Lake in Section 34, where a ridge is crossed by the portage to Birch Lake. This has steep walls on both sides as if it were a dike rather than a sill, and it can be followed by this topographic feature for about a half mile to the west. It then crosses the "old road," the original Gunflint trail, and is cut off by the gabbro. For most of the half mile the ridge is diabase, but near the old road and near the gabbro for about 100 yards it has been changed to hornfels, indistinguishable in the field and in hand specimens from the hornfels derived from slate. The change from diabase to hornfels is clearly shown also on the Mesabi Range, where a small sill can be traced into the contact hornfels by its plagioclase phenocrysts.[15] Similar occurrences are known on Gabemichigama and east of Disappointment Lake, west of the area here mapped.

It is possible that the sills and dikes are not all of the same age. Some may have been injected at the time the gabbro was formed, but no exposures were found to establish such a relation.

The gabbro has been given detailed study elsewhere.[16] Its chief interest here is in the fact that it has recrystallized the Rove slate much more thoroughly than the Logan sills did. It resists erosion somewhat more strongly than the older sedimentary rocks and mixed formations, with the result that the contact is usually marked by an escarpment. Above the bluff, on the gabbro plateau, the banded composition of the gabbro results in a series of minor ridges within the formation, in marked contrast to the larger saw-tooth ridges made by the sills, where each major sill forms a "saw tooth."

The gabbro near the Rove formation is in most places not distinguishable from that in the main areas to the south and west; it preserves its coarse grain and commonly its diabasic fabric to the contact of underlying rocks. At the contact in many places there is a confusion of

the Ninth Annual Report of the Survey, 1881, page 63, really contains the earliest note of an intrusive into the Animikie along the bedding.

[15] F. F. Grout and T. M. Broderick, *Magnetite Deposits of the Eastern Mesabi Range* (Minnesota Geological Survey Bulletin 17, 1919), p. 56.

[16] F. F. Grout, "A Type of Igneous Differentiation," *Journal of Geology*, 26:626–658 (1918).

fragments of wall rock and gabbro (Figure 5), with certain more silicic emanations from the gabbro. These are numerous between East Bearskin and Stump lakes.

In the main area of gabbro are sporadic bands of segregated magnetite, and some such segregations occur in the sill-like extension as far east as Sec. 10, T. 64 N., R. 2 E.

FIGURE 5. — Brecciated hornfels just below the gabbro contact with aplite and miscellaneous inclusions. Gunflint trail just east of Loon Lake.

PLEISTOCENE SERIES

Sedimentary deposits connected with the Pleistocene glaciation are widespread through the area. There is no very thick cover of drift over the hills and slopes, but the thin veneer in many places suggests that glacial deposits lie deeper in some of the valleys and that the lack of adjustment of the drainage, as well as the lakes and the abandoned valleys, may be due partly to drift obstructions across the original drainage.

In the eastern half of the area, near Lake Superior in particular, the Pleistocene deposits are more complex. Ice from the northeast evidently served as a dam holding the waters of the lake at higher levels than the present lake. Beaches and shore cliffs formed at different levels, and there are considerable bodies of lake beds and water-laid moraine. Chief of these deposits is a tough red pebbly clay.[17] It fills many of the older valleys, and the present streams cut steep banks in it, almost as in hard rocks. When thoroughly wet the clay permits a little slipping — miniature landslides — but these do not greatly affect the banks, which are generally steep.

There are also prominent ridges of well-rounded cobblestones high

[17] Frank Leverett, *Moraines and Shore Lines of the Lake Superior Region* (United States Geological Survey Professional Paper 154A, 1929). On page 27 Leverett describes this clay as a "water-laid" portion of the Fond du Lac moraine.

above Lake Superior. Leverett attributes some of these to a glacial stage of Lake Superior called Lake Duluth, which extended far up the valley of Pigeon River. He states that the beaches near Grand Marais lie at elevations of from 1,206 to 1,275 feet above sea level, or 604 to 623 feet above the present beach of the lake. A later glacial lake known as Lake Algonquin formed beaches near Grand Marais at 1,042 above sea level, and as the lakes drained off at several lower levels beaches are noted at 785, 760, 725, and finally 630 feet above sea level near Grand Marais. Since the beaches were formed the region has been tilted, with the result that around Pigeon Point they are a little higher than at Grand Marais; but several of these lower beaches are clearly visible at places on the "Point" and back to Wauswaugoning Bay.

From the Pigeon River Falls to its present mouth at Lake Superior the river is bordered on the south side by a low swamp which extends to Wauswaugoning Bay. When the lake was at a slightly higher stage this area was under water. Pigeon Point was an island, and the mouth of the river was just below the falls. There was no doubt a time when the river emptied into Wauswaugoning Bay. The swampy area is probably a delta deposit.

Many of the valleys in the area are bordered with alluvium, particularly parts of the Pigeon River and the Stump River, a tributary in T. 64 N., R. 3 E. Some of the swampy lakes are rapidly filling with peat, but most of the larger lakes are in deep rock basins, and the levels fluctuate very little.

DETAILED DESCRIPTION OF THE ROVE FORMATION

General Statement

As noted above, the Rove formation lies conformably above the Gunflint iron-bearing rocks and has above it some Keweenawan sandstone and basalt flows with no very marked unconformity. All the phases of Rove, including the formations above and below, are intruded by a complex of dikes and sills of diabase. These rocks, being harder, stand out as ridges, between which the easily eroded Rove rocks occupy valleys. The best exposures of Rove formation are at the bases of cliffs in the north-facing escarpments of a series of saw-tooth mountains. (See Figure 4.)

Most of the Rove formation in northeastern Minnesota seems to be graywacke, grading from a quartzite on the one hand to a thin-bedded argillite on the other. The dominant phase is called slate because the thin beds are so far recrystallized that the slabs do not slake down to clay as do slabs of many shales. The talus of slabs greatly resembles slate, though there is no flow cleavage across the bedding.

The argillite and graywacke are nearly black in most fresh exposures but are gray and green at some places. The quartzites range from gray to nearly white and locally near the intrusives are reddened by feldspar. Nearly all phases are lighter colored in weathered outcrops than in fresh exposures; the average gray slate turns a light gray with commonly a dirty brownish tint.

No reasonably complete section of the formation is to be found. The succession must be generalized from scattered exposures, only a few of which expose a thickness of as much as 100 feet.

In a broad way the change in horizon from the base of the formation to higher beds is exposed in a sequence from Gunflint Lake to Pigeon Point. (See Plate 20.) Most of the exposures in the west, near the base, are black argillite. Those at higher horizons farther east have a higher percentage of quartzite. In practically every large exposure, however, the thin and thick beds, argillite and graywacke, alternate irregularly, and no division of the formation is attempted.[1]

The black phase of the Rove slate is exposed near the contact with the iron formation, on the south side of Cross River near the point where it enters Gunflint Lake. The saw-tooth ridges over most of the area have exposures of both the black slabby phase and the more massive bedded graywacke in a considerable number of cliffs. An excel-

[1] As was suggested by Grant in the *Final Report of the Minnesota Geological and Natural History Survey*, 4:486–487.

lent exposure of the phases characteristic of the upper parts of the formation occurs in the bluff at the southwest edge of the village of Grand Portage. This bluff of sediments is cut by a number of diabase dikes, which probably caused the exposure by resisting erosion, but the dikes have not greatly altered the sediments between. The thin dark beds at the bottom of the bluff are covered by beds of fine-grained sandstone of a peculiar slabby structure and light gray color. In this and apparently above it are other thin beds of darker argillite. The highway bridge across Pigeon River at the point where State Highway No. 1 leaves Minnesota crosses a gorge in Rove slates which affords an excellent exposure of the formation. The beds are fairly typical of the graywacke phase of the formation but are not so massive nor so thick as at certain other places. One small diabase dike may also be seen at the crossing.

A less accessible but very striking exposure is that on Pigeon River just northeast of the upper end of the Grand Portage. The river drops into a gorge along a dike and makes a "hairpin" turn and a long gorge through slates and quartzites.

The textures and minerals of the several phases, slates, graywackes, and quartzites, differ so widely that three descriptions are needed. The changes from one to the other are sharp in some places and gradational at others. The rarer modifications are mentioned under these three heads.

Structure of the Rove Formation

As a whole the Rove formation is a well-bedded series of sediments, but some phases are very thinly bedded, while the coarser phases may have beds many feet thick. The beds in general strike about N. 70° E. and commonly have gentle dips, between 4° and 15°. (See Figure 9.) The irregularities in the ridges are due not so much to variation in dip and strike of beds as to cross-cutting dikes and variations in the thicknesses of sills. Locally near faults and igneous intrusives the attitude of the beds may vary much beyond the limits mentioned. A fairly regular increase in dip is to be noted near the Duluth gabbro, the maximum being almost 45°. In the valley of Stump River, Sec. 10, T. 64 N., R. 3 E., a group of outcrops indicates an anticline and a syncline, which are exceptional in this district, though such variations in structure are reported farther east in the same formation. Minor folds appear in thin zones near intrusions, and it is likely that the slates were folded under stresses that would break or fault the quartzites, lavas, and iron formations.

The larger structure of the slates is brought into relief by the intrusive dikes and sills. The southward-dipping sills from Gunflint Lake to Stump River produce saw-tooth mountains with summits regularly spaced. East of Stump River to Pigeon Point are other sills, but the topography is confused by numerous large dikes. The reason for this

FIGURE 6. — Joints in graywacke, which alternates with bedded slates. Split Rock Canyon, Pigeon River.

FIGURE 7. — Rhombic joint blocks of Rove slate. Shore of Alder Lake, Sec. 11, T. 64 N., R. 1 E.

difference in habit of the intrusive rocks is not clear, but several theories are stated below.

Joints are conspicuous and in places very regular. Most joints are normal to the bedding, and some occur in coordinate systems, one approximately in the direction of the strike and another at right angles. The regularity of closely spaced joints in the more massive graywacke beds is striking (see Figure 6), and many of the talus slopes consist largely of rectangular blocks. In a number of places, however, the angles between the joints may be as low as 60°, and the talus blocks are rhombic. (See Figure 7.) In the thin argillaceous beds the hardened shaly parting dominates, and thin slabs make the talus slopes. At the east end of Clearwater Lake the jointing in the graywacke is very prominent in two, and locally in several, directions, forming rectangular and columnar polygonal blocks of regular forms. (See Figure 8.) Veins are probably guided by prominent joints. They are given detailed discussion below. Many joint planes are conspicuous in freshly broken blocks because of the glistening flakes of secondary muscovite scattered on a dark background.

Faults are known in several places, but the throws are small and the uniformity of the slate makes it difficult to trace a fault unless it throws a sill into contact with slate. (See Figure 11.) A number of normal faults are known in the underlying iron formation [2] and no doubt are present also in the slate. It has been suggested that some of the escarpments result from strike faults, but although they have been searched for, none have been recognized.

FIGURE 8. — Jointing on cliff of graywacke phase of Rove formation. Some blocks are hexagonal columns. East end of Clearwater Lake, Sec. 25, T. 65 N., R. 1 E.

Certain offsets of the sediments were produced before or during the intrusion of the sills, but others offset the sediments and sills together.

An unusual series of interrupted ridges north of East Pike Lake is attributed to a series of hinge faults. The usual slope, rising to the north, is here crossed by a series of transverse valleys with a bluff on the west side and a gentle slope on the east side of the valley. The effect is as if the regular sawtooth ridge running east had been broken into four or five blocks at the upper end and each block twisted down at the west but not disturbed at the east. (See Figure 12.) The sills dip west locally but swing around near the foot of the slope to the usual southerly dip. At the chain of lakes south of the area described, all the beds seem to join in the regular series running east and west. (See Plate 10.)

[2] J. E. Gill, "Gunflint Iron-bearing Formation, Ontario," Summary Report of the Geological Survey of Canada, 1924, Part C, p. 40.

Thickness of the Rove Formation

The thickness of the Rove formation in Minnesota is not determinable in any single cross section. At the west end of the district the Duluth gabbro cuts into the upper parts of the slate and at the east the larger part of the formation is on the Canadian side of the boundary. A section from Moose Lake to Stump Lake indicates about 3,000 feet of rock thickness, half of which is believed to be slate and

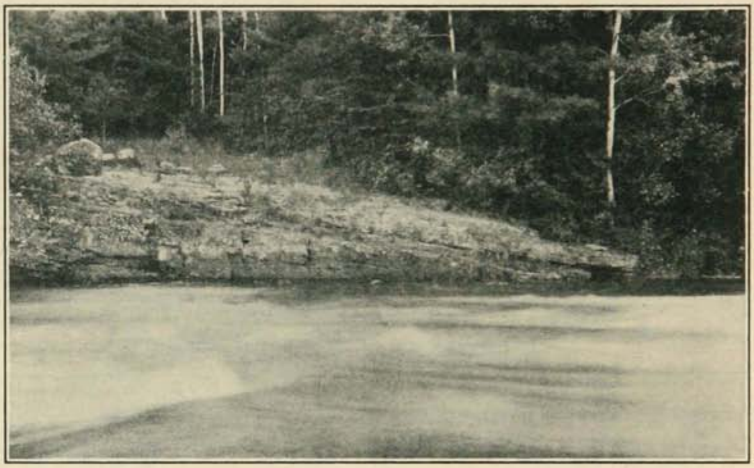


Figure 9. — Slate beds just above Partridge Falls, Pigeon River, dipping south at a low angle.

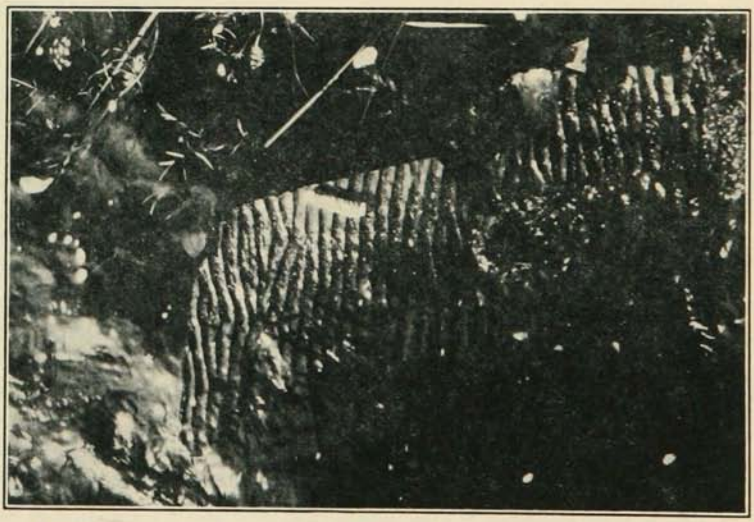


Figure 10. — Ripple marks in Rove slate, at water's edge just above Partridge Falls, Pigeon River.

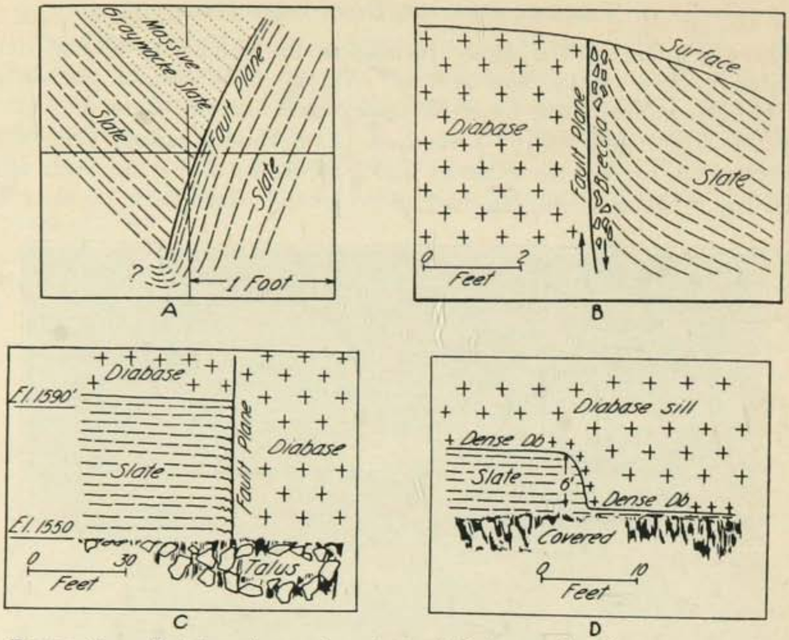


FIGURE 11. — Sketches of several contacts of diabase and sediments.

A. Fold and fault, NE¼ Sec. 15, T. 64 N., R. 3 E.

B. Fault and breccia zone at exploration shaft on shore of McFarland Lake, NW¼ Sec. 5, T. 64 N., R. 3 E.

C. Fault on cliff facing North Fowl Lake, 500 paces north of southeast corner of Sec. 27, T. 65 N., R. 3 E.

D. Diabase with chilled margin cutting across the bedding of Rove slate, NW¼ Sec. 3, T. 64 N., R. 3 E.

half diabase sills. This overlies a considerable thickness in Canada, where there may be as much as 2,500 feet of slate and diabase along Arrow Lake. The total slate along this section may be roughly 2,800 feet thick, and the sills are so numerous and large that they add another 2,800 feet to the combined series. Grant[3] made a similar estimate based on an average dip of 10°, but there are few dips as great as this except very locally near the gabbro. Grant's estimate was based on the assumption that the sills made only about one-tenth of the thickness of the combined formations, whereas detailed maps indicate that at least half of the section is made up of sills. The slate was probably not over 3,000 feet thick, therefore, when the Keweenawan covered it in this area. To the northeast Tanton finds that the slate, perhaps as much as 2,000 feet thick, pinches out to 20 feet northeast of Thunder Bay, about 55 miles from the Minnesota exposures. If the original deposit was thicker to the southwest, as this indicates, it is consistent with the estimates of

[3] U. S. Grant, *Final Report of the Minnesota Geological and Natural History Survey*, 4:486.

great thicknesses of the Animikie slates on the Mesabi Range and the estimate of a thickness of 13,000 feet on the Gogebic Range.

The Black and Gray Argillite (Typical "Slate")

The black slates are graphitic and the gray rocks are darkened, probably by graphite. In the lower beds graphite may constitute 2 to 5 per cent of the rock and obscure other minerals because of its lack of transparency. It can be burned out at high temperatures, leaving a lighter residue. The bedding of the slate is very thin, but beds in the coarser graywacke may be several feet thick. Locally certain beds are cherty or calcareous. Several large slabs in the talus slopes show peculiar markings along the bedding that resemble obscure fossil plants, but no plants

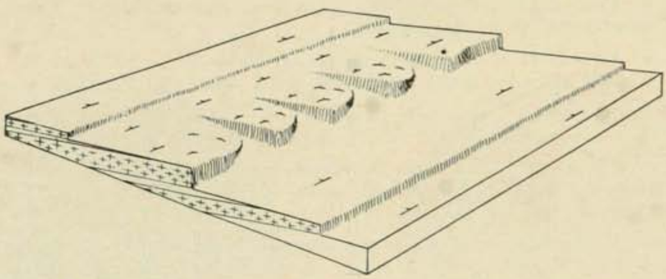


FIGURE 12. — Diagrammatic sketch of "rip saw" structure.

or other fossils have been identified, and the markings may originate in other ways. Tanton has described structures that seemed to have resulted from flow of mud.

The texture is very fine. (See Figure 13.) Fragmental angular grains that have not been recrystallized are from .01 to .05 millimeters across, but these probably lay originally in a matrix of clay and organic matter that was partly colloidal. The grain size differs in alternating beds, which in many places are visible as bands in thin sections.

The minerals of the fine slates are too minute for satisfactory identification but may be estimated from the fact that the graywackes with coarser recognizable minerals have about the same chemical composition. Quartz, feldspar, biotite, chlorite, and graphite are dominant; carbonate and sulphides appear locally. The hardness, luster, and fracture of certain phases make it certain that there is some chert in a few thin beds. Several exposures on John Lake (T. 65 N., R. 3 E.) have beds with a granule texture resembling the greenalite granules of the underlying iron formation. The beds in thin sections show not only different sizes of grain but a concentration of biotite in the finer and quartz in the coarser bands.

The gradation from these slates to the contact metamorphic zone is in many cases marked by the development of "ghosts" of cordierite

FIGURE 13. — Typical slate from west end of Gunflint Lake near Cross River. Mag. x 50.

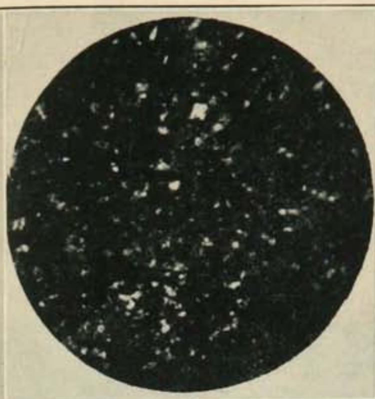
FIGURE 14. — Graywacke phase of Rove formation. Sec. 35, T. 65 N., R. 2 W., south of Daniels Lake. Mag. x 50.

FIGURE 15. — Quartzite phase of Rove formation. From quarter corner on east line of Sec. 6, T. 65 N., R. 1 W. Mag. x 65.

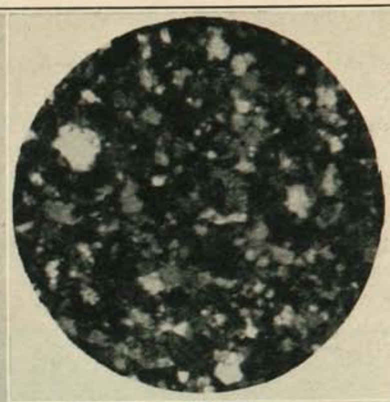
FIGURE 16. — Cordierite metacrysts developed in Rove slate underlying a thick diabase sill south of Rover Lake in Sec. 6, T. 65 N., R. 1 W. Mag. x 50.

FIGURE 17. — Quartzite metamorphosed at contact of large dike. Graphic intergrowth of quartz and feldspar developed around quartz grains and encroached on them. Sec. 34, T. 64 N., R. 6 E. Mag. x 95.

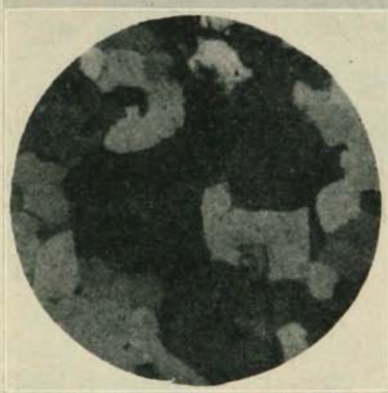
FIGURE 18. — Hornfels texture developed in contact rock as the result of contact metamorphism of Rove slate by Duluth gabbro. Sec. 7, T. 64 N., R. 5 W. Near Lake Gabemichigama. Mag. x 26.



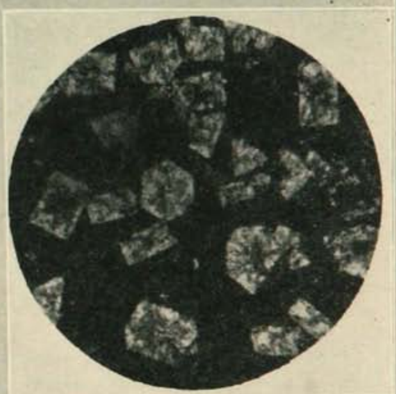
13



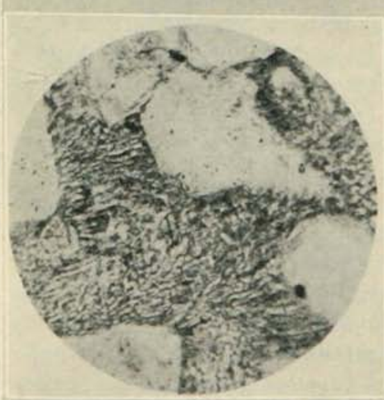
14



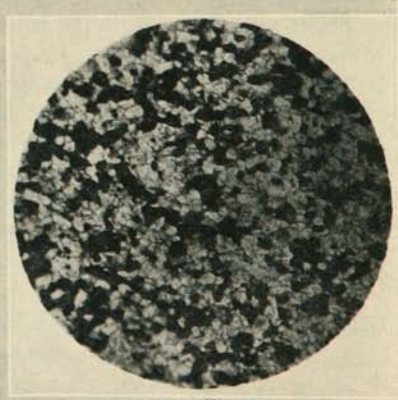
15



16



17



18

crystals, hazy, ill-defined, light patches in the granular dark field. These still include many grains of the same kind as the surrounding field and may be dusty with graphite. They have no regular outlines, but considerable parts if not all of the light material of the ghost extinguishes at once, and there are gradations from them to good metacrysts of cordierite (see Figure 16), so their identification is satisfactory. The lighter slates, which are free from graphite, seem to have no such cordierite.

FIGURE 19. — Large concretion in graywacke quartzite on Pigeon Point, Sec. 31, T. 64 N., R. 7 E., eroded by wave action more rapidly than its matrix.

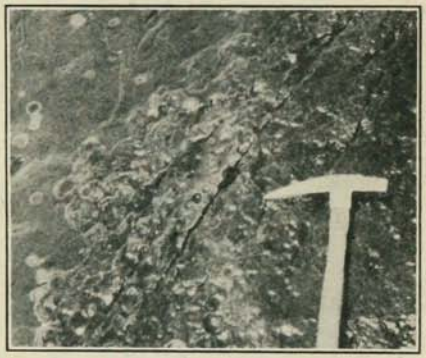


FIGURE 20. — A group of small concretions in quartzite on Pigeon Point, Sec. 31, T. 64 N., R. 7 E.

No extensive beds of limestone have been identified in the Rove formation in Minnesota, although a limy bed marks the transition from the Gunflint iron-bearing beds to the black slate.[4] There are, however, some thin beds with enough carbonate to produce contact-metamorphic garnet-carbonate rock.

There are also a number of beds with sufficient lime to furnish limy concretions up to 2 feet wide. These may be seen on the banks of Pigeon River in Sec. 3, T. 64 N., R. 5 E., and on the shore of Lake Superior near the islands south of Pigeon Point. (See Figures 19 and 20.)

Probably these are at different horizons, but no single exposed section has been noted with concretions at more than one horizon. The concretions are oblate spheroids, or discs, parallel to the bedding. Many are fairly symmetrical, but some are flatter on the upper or lower side. Along the shore of Lake Superior, wave action has scoured out the calcareous concretions more rapidly than the quartzite matrix and left pits that resemble potholes. Broken spheroids commonly show cone-in-cone structures, which students of concretions attribute to the action of pres-

[4] T. M. Broderick, "Economic Geology and Stratigraphy of the Gunflint Iron-bearing Formation," *Economic Geology*, 15:422–450 (1920). J. E. Gill notes some limestone on the Canadian side in "Gunflint Iron-bearing Formation, Ontario," Summary Report of the Geological Survey of Canada, 1924, Part C, p. 37 c.

sure on the softer calcareous material. No septarian structures were noted in Minnesota, but Tanton reports them in this formation in the Thunder Bay region.[5] From the way the bedding runs through them, bulging only slightly, Tanton believes that the concretions formed after the rock was bedded but while it was still soft.

Much of the jointed slate has some secondary muscovite and probably other minerals along the joint surfaces.

The composition of unaltered slate is indicated by the analyses shown in Table 1.

TABLE 1. — ANALYSES OF ANIMIKIE SLATES

	1	2	3
SiO_2	64.77	58.04	62.26
Al_2O_3	14.45	18.66	16.89
Fe_2O_3	1.84	1.51	1.76
FeO	4.54	5.98	4.55
MgO	2.34	3.24	2.95
CaO	2.33	1.02	.42
Na_2O	1.37	2.12	2.29
K_2O	5.03	3.28	3.02
H_2O-	.07	.38	.70
H_2O+	1.92	3.28	3.88
TiO_2	.60	.71	.60
P_2O_5	.20	.12	.20
MnO	.11	.08	..
SO_3	.60	.70	..
CO_2	.41	.14	None
ZrO_2	...	.13	..
BaO	...	.44	..
Organic	...	.56	..
S	...	.17	..
Total	100.58	100.56	99.52

1. Rove slate–mica schist, bed of Cross River near Gunflint Lake. United States Geological Survey Bulletin 591, p. 73. T. M. Chatard, analyst.
2. Drill core of Virginia slate, Sec. 1, T. 57 N., R. 17 W. George Ward, analyst.
3. Composite of Virginia slate. C. K. Leith, United States Geological Survey Monograph 43 (1903), p. 170.

THE GRAYWACKES

Graywacke beds occur throughout the whole Rove formation from the lower black slaty beds to those just under the "Puckwunge," basal Keweenawan conglomerate. They form the greatest bulk of the material in the central part of the Minnesota exposures, above the lower slaty zone and below the upper quartzites.

The graywacke in particular shows regular blocky jointing. (See Figures 6, 7, and 8.) The joint faces commonly are coated with secondary minerals, muscovite, quartz, and epidote.

[5] Tanton, *Fort William and Port Arthur, and Thunder Cape Map Areas* (Memoir 167, Geological Survey of Canada, 1931).

The graywackes grading from slates are almost black because of black carbonaceous matter and other black grains, such as occur in the slates. Locally they are found in minor beds, green, brown, or gray in color. They form coarse beds from 1 to 4 feet thick, and in many cases they are remarkably like basalts in outcrops. It is often difficult to find the contact of a chilled diabase with the sediments. A few beds show ripple marks. (See Figure 10.) Many are cross-bedded, though only on a small scale, as is especially well shown near the outlet of Pine Lake.

The common grains range from about .1 millimeter to .5 millimeter in diameter, but some are coarser, while others are as fine as grains of slates. (See Figure 14.) Most of the grains are angular to sub-rounded fragments of quartz, and they lie in a recrystallized cement of the argillaceous and ferruginous portion of the original sediment. Possibly half

TABLE 2. — ANALYSIS OF GRAYWACKE *

SiO_2	82.15	K_2O	1.09
Al_2O_3	5.37	Na_2O	1.84
Fe_2O_3	1.47	H_2O-	.07
FeO	1.08	H_2O+	.74
MgO	2.22	TiO_2	.35
CaO	1.85		
		Total	98.23

* Graywacke phase of the Rove formation from east line of Sec. 33, T. 65 N., R. 3 W., just south of Loon Lake. D. M. Davidson, analyst.

the specimens selected for study show a little secondary enlargement of the sandy grains. Flattened mud or shale lumps up to an inch or more across are very common and easily found in the field.

Quartz constitutes some 50 to 60 per cent of most of the graywackes, with feldspars, biotite, chlorite, and graphite as common essential minerals. Much of the chlorite seems to be a direct product of recrystallization, but some is derived from recrystallized biotite. Part of it is radially distributed around sandy grains of quartz and feldspar. Locally certain beds of graywacke contain sericite, calcite, chert, hematite, leucoxene, and sulphides. Near the igneous intrusives are small amounts of cordierite and even tourmaline. Rock fragments in sandy grains suggest that parts of the rock may be tuffaceous.

A few plagioclase grains are as calcic as andesine and suggest that the source of the materials for the sediment included some basic igneous rocks as well as quartz rocks.

Sericite occurs in two ways, as a hydrothermal patch of alteration products from the feldspar and as minute needles or radial groups in the cement.

As quartz becomes more abundant these rocks grade into quartzites, some of which have less graphite and are lighter colored.

The composition of the graywackes is no doubt variable, but it is indicated by the analysis in Table 2.

The Quartzites

Gray, white, and pink quartzites are prominent, especially in the eastern part of the area, but extend west in certain beds as far as Loon Lake. Typically they form massive beds that may be several feet thick but that grade into slates and alternate irregularly with thin beds. Topographically the quartzites form ridges that are almost like the

FIGURE 21. — Peculiar jointing and bedding of sandy phase of the Rove formation, Stump River.

ridges formed by sills and very much in contrast with the depressions underlaid by slate. They are jointed in rectangular blocks, one set of joints trending about north and south and the other east and west.

The original sediment was probably a nearly white sand in many cases, and the colors are due to cement or to alteration. The luster of fresh gray rocks is notably vitreous. Certain thin beds near State Highway No. 1 in Sec. 26, T. 64 N., R. 5 E., and from there to Pigeon Point have pebbles of quartz and granite [6] up to an inch in diameter, but they do not seem to mark any important time interval or change in conditions of sedimentation. Several beds show a peculiar mottling, with half-inch spots of green in a pink matrix.

Many outcrops from Stump River to Pigeon Point show a peculiar slabby parting with slightly curved surfaces. (See Figure 21.) At first glance these suggest the curves of cross-bedding, but a close inspection does not furnish any strong confirmation of that origin for the structure. Possibly it should be attributed to the filling of shifting shallow chan-

[6] Bayley, *op. cit.*, p. 61.

nels. It is widespread in the Rove quartzite, and a similar structure can be seen in the sands of the basal Keweenawan sediments. Figure 22 shows the genuine cross-bedding of the Keweenawan.

True cross-bedding appears in some of the lighter quartzites on Pigeon Point, and ripple marks are not uncommon. The sand grains vary in size from .05 to .5 millimeters in diameter. They are rarely coarser except in the thin local pebbly beds. Some of the original grains were apparently angular and others rounded; but the grains are now modified by some secondary growth and a good deal of recrystallization to a mosaic, or a sutured interlocking texture. (See Figure 15.) The original grains are outlined now by a faint dusty line of liquid and gas inclusions.

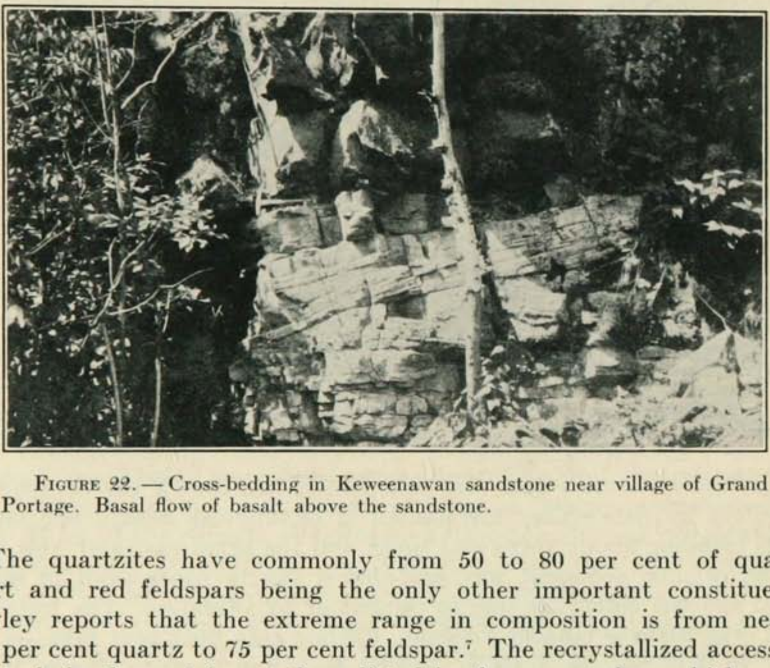


FIGURE 22. — Cross-bedding in Keweenawan sandstone near village of Grand Portage. Basal flow of basalt above the sandstone.

The quartzites have commonly from 50 to 80 per cent of quartz, chert and red feldspars being the only other important constituents. Bayley reports that the extreme range in composition is from nearly 100 per cent quartz to 75 per cent feldspar.[7] The recrystallized accessory minerals in the matrix are those listed in the graywackes, which grade into these quartzites by all intermediate stages. Biotite and chlorite are common and sericite and graphite occur in some places. The sericite has locally a greenish color. A few grains of tourmaline, epidote, magnetite, zircon, apatite, or pyrite may be seen. Weathering has produced some kaolinite and hematite dust that reddens the feldspars, and alteration has left scattered leucoxene. Cordierite appears only in the rocks approaching graywacke and affected by contact action. The feldspars are red and most of the grains are too dusty for accurate identification. A few grains show the twinning of plagioclase.

[7] Bayley, *op. cit.*, p. 69.

Concretions of calcite, and some marked by epidote that probably resulted from alteration of the calcite spots in the sandstone, were described in detail by Bayley.[8] Those over a few inches across have a cone-in-cone structure, as noted in the concretions found in the slaty phase.

The compositions of the prevalent fresh quartzites are indicated by the analyses shown in Table 3.

TABLE 3. — ANALYSES OF LITTLE-ALTERED QUARTZITES

	1	2	3	4
SiO_2	74.22	73.65	73.64	81.86
Al_2O_3	10.61	11.08	11.25	9.87
Fe_2O_3	7.45	7.24	6.24	1.44
FeO	.85	.77	1.04	2.36
MgO	1.48	1.52	1.57	.86
CaO	.56	.40	.36	.46
Na_2O	2.12	1.67	3.04	1.61
K_2O	1.08	1.65	1.42	.45
H_2O	1.79	1.88	1.98	1.43
TiO_2	.16	trace	trace	...
MnO	...	trace	...	...
Total	100.32	99.86	100.54	100.29

1. Dark vitreous quartzite from the little peninsula on the south shore of Pigeon Point. W. S. Bayley, United States Geological Survey Bulletin 109 (1893), p. 69. R. B. Riggs, analyst.
2. Interbedded lighter quartzite. *Ibid.*, p. 69. R. B. Riggs, analyst.
3. Unaltered quartzite at Pigeon Point. *Ibid.*, p. 84. R. B. Riggs, analyst.
4. Quartzite from hill in NE¼ Sec. 25, T. 64 N., R. 6 E. *Final Report of the Minnesota Geological and Natural History Survey,* 5:288. C. F. Sidener, analyst.

ORIGIN OF THE ROVE FORMATION

Many parts of the Rove formation seem to be slightly altered sediments like those that are being deposited today — carbonaceous shales, sandy shales, and sandstones. The carbonaceous material has produced no fossils that have been identified, and this material may be a product of microscopic vegetation. The presence of considerable graywacke and the abundant fragments of igneous rock in some of the sands suggest that volcanic tuffs, more or less worked over, may have contributed parts of the series.

CONTACT ALTERATION BY SILLS AND DIKES

About half the volume of rock in the limits of the Rove formation consists of intrusive diabase and its differentiates. These are so thickly scattered that it would seem as if no part of the sediment could have escaped the contact metamorphism they must have caused. Nevertheless, contact effects are surprisingly slight over much of the area. Many

[8] Bayley, *op. cit.*, p. 70–77.

of the sills are thin, and it is possible that they were not all intruded at one time; one may have cooled before the next added to the general heat. The results vary greatly according to the character of the original bed, even in different beds of black slate that are megascopically similar. A few of the dikes and the larger sills have some noteworthy contact zones.

Alteration of slates and graywackes by intrusives.—The black sediments at the contacts with sills and dikes are slightly hardened and massive, although probably some of them were originally thinly bedded and cleaved. At the upper contacts, now well exposed in many of the dip slopes of diabase sills, there was a local crumpling of the beds, as if the material were greatly deformed, perhaps even rendered "mushy" by magmatic heat. Such a crumpled zone, however, is very thin, probably not over an inch in thickness near most of the sills. Near some of the dikes, the slates are crumpled for several feet, in contrast with the thin zone at sill contacts. Bayley records that crumpling occurred two or three feet from an igneous rock, even in a hard quartzite layer.

Mineralogically the only common feature of the contact slates and graywackes is the increase in pyrite, which is found in small crystals. Two other minerals, cordierite and andalusite, appear locally as metacrysts. These are attributed to contact action and seem to have formed only in beds of a certain character, not at all generally through the black slate contact zone. Some prominent andalusite metacrysts occur as white needles one-fourth of an inch long in beds of black slate as much as 20 feet below the larger sills, which are 100 feet or more thick. The beds for 20 feet above the sills are rarely exposed but probably were affected in a similar way. This condition seems to indicate fairly well the extent of general metamorphism by the sills. Between the beds having metacrysts and the pyritic contact the slates show little sign of alteration in the field.

Microscopically the slates near the sills may be slightly coarser than the average slate, but the most conspicuous change is the development of metacrysts. These appear first as "ghostlike" spots of lighter color in the mixed fine-grained slate. As they develop they gradually eliminate more completely the quartz, biotite, etc., and assume the shapes of cordierite (see Figure 16) or in a few cases of andalusite. Such metacrysts may constitute over 50 per cent of some of the contact slates. The cordierite grains rarely grow larger than a millimeter in diameter, but the andalusite needles may be a millimeter thick and up to 10 millimeters long. Many contain carbonaceous inclusions regularly arranged. These metacrysts are partly altered later by hydrothermal action, but the fresher ones still show cores of the metacrysts, and the forms are characteristic. (See Figure 23.) The most altered specimens contain in some cases not only metacrysts but also large muscovite and biotite flakes, poikilitically enclosing recrystallized grains of the main slate minerals. Similar cordierite hornfels is known from the Virginia slate on the Mesabi Range.[9]

Tourmaline, apatite, and probably enstatite have been noted, each in a single specimen of altered slate near a sill, but it is not certain that they are results of contact action. One banded specimen from near E¼ corner Sec. 22, T. 65 N., R. 1 E., shows striking variations in five or six layers; chert, slate, graywacke, and carbonate bands occur in turn, and some zones are rich in epidote and some in garnet. In such rocks the effect may have been unusually pronounced because the beds lie between two sills. The rocks are exceptionally rich in carbonate, however, and the pronounced change may be due to the abundance of easily altered carbonate rather than to excess of heat. Garnet is reported in some limy slate in Canada near by.[10]

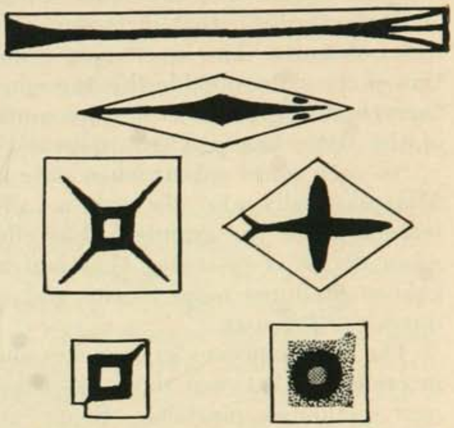


FIGURE 23. — Sketches of andalusite in thin section.

Besides the intense alteration between two closely spaced sills there is a similar strong alteration along some especially large dikes and between closely spaced parallel dikes of diabase. Such parallel dikes are common features of the eastern part of the district, and the contact rocks are commonly recrystallized quartzite (see Figure 17); but in a few places slates have been caught in similar positions and have been altered to hornfels as thoroughly as by the larger gabbro intrusion. (See the discussion of gabbro effects on pages 33 to 35.) A particularly good example is a hornfels outcropping in a northward-facing cliff 150 paces south of the center of Sec. 34, T. 64 N., R. 5 E., reached by a short walk from a farm road. Most of the rock is made up of a brown, sugary, grained mixture of biotite, quartz, and feldspar, with a little magnetite and a good deal of yellowish chlorite. The quartz and feldspar are partly recrystallized into a graphic pattern, but where biotite and chlorite are abundant the granoblastic or hornfels texture dominates over any tendency to be graphic. Perhaps this thorough recrystallization near dikes may be attributable to the heat brought to the dike walls, not only by the dike material now occurring near, but by the larger quantities of magma passing through the fracture that fed the sills or larger chambers.

[9] C. K. Leith, *The Mesabi Iron-bearing District* (United States Geological Survey Monograph 43, 1903), p. 171. The contact action is referred to the gabbro by Leith, but the rock is apparently in close contact with a sill and several thousand feet from gabbro.

[10] J. E. Gill, "Gunflint Iron-bearing Formation, Ontario," Summary Report of the Geological Survey of Canada, 1924, Part C.

On Pigeon Point more than elsewhere in the area there is a red granitic phase of the intrusive sills, and near this the slates show a somewhat different alteration. The chlorite and sericite content is large, and some red feldspar metacrysts have been formed in the chlorite schist. These metacrysts appear to have been introduced from the magma but may include in their substance some of the constituents of the slate.

Bayley notes [11] that inclusions of slate in red rock (granite) show a series of zones. The inner mass is chlorite schist from the recrystallization of the slate; outside this the schist is impregnated with red feldspar; then there is granite with some contamination by the dark constituents of the slate; finally a true red-rock granite.

No such zones appear when slate is enclosed in the diabase or gabbro. Mineralogically also the gabbro affects the sediments somewhat differently from the granite. Mild effects may be indistinguishable, but when action is so strong that material is added from the magma, the gabbro produces more biotite and even augite, while the granite produces red feldspar.[12]

The more siliceous graywackes show mineralogic and textural effects intermediate between those described for slates and those noted in the next section as quartzites. Some "graphic" intergrowths of quartz and feldspar form in certain beds that alternate with dense altered slates as hornfels. (See Figure 17.)

The composition of the slates altered near sills is shown by the analyses in Table 4.

TABLE 4. — ANALYSES OF ALTERED SLATES

	1	2	3
SiO_2	64.45	59.71	63.82
Al_2O_3	17.36	18.32	14.65
Fe_2O_3	2.44	8.11	3.16
FeO	.30	.85	5.12
MgO	2.84	3.54	2.08
CaO	.53	1.05	.70
K_2O	4.44	3.43	2.81
Na_2O	2.11	1.93	1.95
H_2O-	.76	3.24	2.62
H_2O+	2.41		
TiO_2	.45	trace	2.66
Carbon	2.59	...	P_2O_5 .19
			SO_3 .33
Total	100.68	100.18	100.09

1. Cordierite slate from west line of Sec. 24, T. 65 N., R. 3 W., just south of Gunflint Lake below diabase sill. D. M. Davidson, analyst.
2. Rove slate slightly altered by diabase dike three-fourths of a mile west of the little isthmus at Pigeon Point. United States Geological Survey Bulletin 109, p. 84. R. B. Riggs, analyst.
3. Purple altered slate at Pigeon Point. *Ibid.*, p. 90. J. E. Whitfield, analyst.

[11] *Op. cit.*, p. 79. [12] Bayley, *op. cit.*, p. 100.

Alteration of quartzite near intrusives.—The sills of moderate size affect the quartzites about as little as they do the slates, their chief effects being a little recrystallization and a destruction of the original grain outlines and secondary growth. The texture varies from a mosaic to a sutured intergrowth.

The larger sills, however, produce more notable effects, and the largest of all, that on Pigeon Point, has such important and striking effects that it has been the subject of several studies and has been referred to so often that Pigeon Point has become a classic locality for the study of the mutual relations of diabase and quartzite.[13] Bayley described the rocks of Pigeon Point in careful petrographic detail and much of the present detail is based on his work.

Between the vitreous quartzites and the igneous rocks to the north is a series of altered rocks of variable width and character. Along much of the belt the igneous rock farthest south is diabase, but in the eastern part of the peninsula there is a red granitic rock and some rock intermediate between that and a diabase. The changes are most striking where red granite is in contact with the quartzite, but they seem to be of the same general nature throughout. Bayley distinguishes three zones of intensity of contact action where red granite is in contact with quartzite, but one or more of the zones may be absent at gabbro contacts.[14]

As a rule the quartzite next to the red granite is reddened and injected intricately by red dikes. Such contacts are not numerous, but the red granite is clearly intrusive and includes fragments of quartzite. At most exposures the contact of granite and quartzite may easily be determined, but since the quartzite is reddened and the red granite shows a platy parting that looks like bedding, the two rocks at some places bear such a strong superficial resemblance to each other that the contact can be determined only by close observation.

The material of one thin section also has not been certainly determined;[15] it has hypersthene and some graphic intergrowth of quartz and feldspar in a mass chiefly quartz, in a granular quartzitic aggregate. Possibly the hypersthene developed as a result of contact metamorphism of the quartzite, but if so the action probably involved emanations from the gabbro magma.

Notwithstanding these difficulties the quartzite may be clearly distinguished from the granite in the great majority of exposures. The contact is not normally gradational even though the quartzite occurs

[13] Bayley, *op. cit.;* R. A. Daly, "The Geology of Pigeon Point, Minnesota," *American Journal of Science,* 4th series, 43:423–448 (1917); F. F. Grout, "Anorthosite and Granite as Differentiates of a Diabase Sill on Pigeon Point, Minnesota," *Bulletin of the Geological Society of America,* 39:555–578 (1928).

[14] *Op. cit.,* p. 79.

[15] N. H. Winchell, *Final Report of the Minnesota Geological and Natural History Survey,* 5:451, Rock no. 618.

in the granite as partially assimilated xenoliths, and the granite has given off red emanations into the contact quartzite.

The mineralogic changes in the quartzite are slight, though they are not accurately determinable because of the variable nature of the original. The proportion of sericite varies with the original proportion of clay. Most of the original sericite and chlorite becomes feldspar and biotite; graphite is prominent locally and forms rounded pellets or fills fractures. Various accessory minerals remain, and some may be enlarged during recrystallization. The feldspar is commonly silicic but in some rocks has an index greater than the quartz with which it is intergrown. Bayley gives analyses of average and reddened quartzites and concludes[16] that red feldspar was added from the granite magma, as the field evidence suggests.

The textural changes, which are more striking, are indicated by Figures 24 A to 24 D.

In thin sections of the freshest vitreous gray quartzite the quartz and some feldspar show clear evidence of their fragmental nature. (See Figure 24 A.) The rock, however, is so rich in feldspar that there is very little secondary growth of the quartz grains, and the cementation is more a matter of recrystallization of feldspar than of added silica. The effects of the intrusive are not regularly zoned but are nevertheless clearly to be noted in the sections near the contact. Any one thin section may show in different parts, different degrees of change from the original texture and minerals. It is only in a broad way that the greatest change is found to be nearest to the intrusive, for apophyses from the main intrusive penetrate the sediment in the most intricate network of irregular dikes and ribbons.

The first step in the change is probably the recrystallization of some of the quartz grains so that they lose their evidently fragmental character. A few grains in thin sections seem to be quite well-formed bipyramidal crystals, but the outlines of many are so embayed as to resemble corroded phenocrysts. It is not likely, however, that the crystals were ever euhedral and corroded; the recrystallization of two minerals simply left the grains with boundaries that resemble the effects of corrosion. (See Figures 24 B and 24 C.) The feldspathic matrix contains some twinned feldspar in the larger grains and some graphic intergrowth, but it does not contain euhedral or zoned grains, such as are found in the intrusive red rock (granite). Bayley notes[17] that some zircon crystals extend from one quartz grain into another, a fact that indicates strongly that the quartz of original fragments has wholly recrystallized in some of the most altered rock.

In extremely altered rocks so little of the original texture remains that the thin sections are mostly graphic intergrowths of quartz and feldspar with considerable ferromagnesian material, rocks closely re-

[16] *Op. cit.*, p. 12, 98.
[17] *Op. cit.*, p. 95–96.

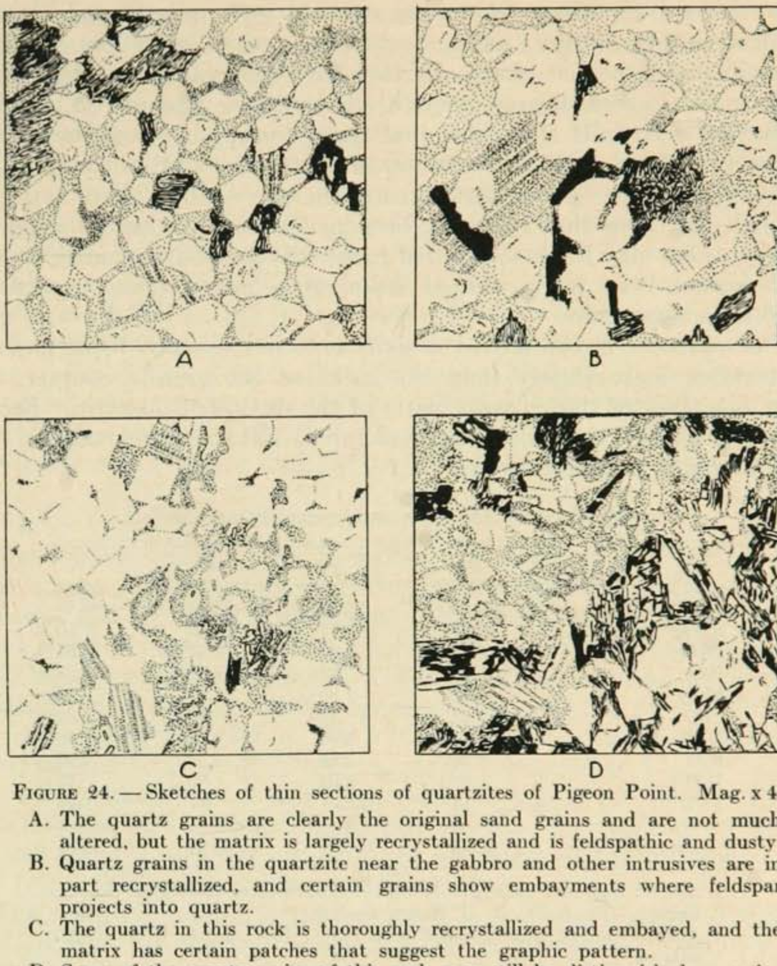


FIGURE 24. — Sketches of thin sections of quartzites of Pigeon Point. Mag. x 45.

A. The quartz grains are clearly the original sand grains and are not much altered, but the matrix is largely recrystallized and is feldspathic and dusty.
B. Quartz grains in the quartzite near the gabbro and other intrusives are in part recrystallized, and certain grains show embayments where feldspar projects into quartz.
C. The quartz in this rock is thoroughly recrystallized and embayed, and the matrix has certain patches that suggest the graphic pattern.
D. Some of the quartz grains of this rock may still be distinguished as grains in a feldspathic matrix, but the quartz has a pattern of feldspar inclusions and the matrix has a pattern of quartz inclusions.

sembling the red igneous rocks. (See Figure 24 D.) The field evidences are more conclusive than the microscopic character of the rocks that they are altered sediments.

The second and in some cases the inner and hotter zone of contact action includes a series of mottled and spotted rocks.[18] Since some of the unaltered quartzites have carbonate concretions, the spots in the altered rocks are not easy to interpret. It is evident, however, that there are spots of more than one kind. Besides the concretions, more or less altered to epidote, there are blotches of red and green colors.

[18] Bayley, *op. cit.*, p. 71–78, 85–92, 97.

Near the red intrusive, where the contact rock is reddened, it may retain some green or gray patches, which seem to be more like unaltered quartzite than the red phase. Farther from the intrusive, where most of the rock is greenish gray, there are a few more altered red blotches. As Bayley says,[19] "It is possible that the red groundmass of these rocks has recrystallized with the addition of feldspathic substance from the red rock, while the green mottlings are the recrystallized residue of the original quartzites that have not been penetrated by the red magma." Finally, there may be some mottled rocks that are contaminated igneous rocks rather than really altered sediments — mixed rocks that never became homogeneous.

The quartzite in the second zone, though not sharply distinct, shows its bedding more clearly than the rocks at the granite contact, and there is a trace of the vitreous luster of the unaltered quartzite. Bayley noted (page 89) that some rocks of mixed slate and quartzite in this zone assumed a purple color.

TABLE 5. — ANALYSES OF ALTERED QUARTZITES

	1	2	3	4
SiO_2	71.00	72.25	73.14	83.69
Al_2O_3	12.88	10.73	12.60	7.50
Fe_2O_3	6.69	8.01	7.57	1.81
FeO	.65	.38	1.31	.38
MgO	1.68	1.85	1.67	.35
CaO	.21	.42	.43	.39
Na_2O	1.43	2.03	1.78	2.46
K_2O	2 95	2.56	1.00	2.61
H_2O+	2.03	2.05	.83	.72
TiO_2	.44	trace	.04	trace
Total	99.96	100.28	100.37	99.91

1. Altered quartzite at Pigeon Point. United States Geological Survey Bulletin 109, p. 84. R. B. Riggs, analyst.
2. Altered spotted quartzite at Pigeon Point. *Ibid.*, p. 84. R. B. Riggs, analyst.
3. Epidote rock derived from quartzite at Pigeon Point. *Ibid.*, p. 76. R. B. Riggs, analyst.
4. Brilliant red quartzite inclusion in contact belt. *Ibid.*, p. 98. Analyst unknown.

On the southern side of the Pigeon Point sill there are a few places where rock of intermediate composition or even gabbro intrudes the sediments and includes fragments of it. Here is an especially interesting occurrence of red rock (granite) in a zone of a few inches around quartzite fragments.[20] A glance at the field occurrence suggests at once that the granite is a result of fusion or "ultrametamorphism" of the quartzite, and there are several things that indicate a close relationship between the granite and the quartzite,[21] the most important of which is the presence of graphic intergrowths of quartz and silicic red feldspar.

[19] Bayley, *op. cit.*, p. 96, 97. [20] *Op. cit.*, p. 110. [21] Daly, *op. cit.*, p. 437.

The possible relationships are discussed in the description of the sills, pages 36 to 59 below. The conclusions reached are that on the whole the series of textures sketched indicate clearly that some graphic quartz-feldspar intergrowths developed by recrystallization in the contact rock. It cannot be said at present that there were no additions of magma or magmatic emanations; probably such emanations aided in the recrystallization. Probably some quartzite was assimilated in the magma, but the granite magma owes only a little to that assimilation.

The principal difference between the analyses of Table 5 and those of the quartzites of Table 3 is in the figures for potash, K_2O. The larger quantity of potash in the contact-altered rocks suggests an addition of potash from the red rock (granite) magma, which evidently was much richer in this element than the gabbro magma. It is noteworthy that in all other constituents the altered rock is very much like the fresh quartzite far from the intrusive. Quartzites in other regions have been feldspathized in a way to indicate that magmatic additions are not rare.[22]

Contact Effects of the Duluth Gabbro

For varying distances up to half a mile from the Duluth gabbro, most of the sediments have been metamorphosed, some of them very greatly. The first sign of change as one approaches the gabbro is the appearance of small seams of a siliceous character that weather out as little ridges on exposed surfaces. These rocks are found on microscopic examination to be considerably recrystallized, and the recrystallization is greater nearer the gabbro. For a few feet at the contact all rocks are recrystallized to a hornfels texture. (See Figure 18.) The slates and graywackes show this change to hornfels very clearly. The quartzites in a few outcrops develop similar textures but have a tendency to be coarser grained; they are distinguished with difficulty from some aplitic and pegmatitic stringers related to the gabbro.

The change in texture in the sediments is shown in Figures 13 and 18. The grain of the hornfels varies in different specimens from .05 to .7 millimeters. Occasional poikilitic grains of biotite or others may be more than a millimeter across. If augite is coarse the texture approaches somewhat that of a diabase. The bedded structure of the slate is not wholly lost.

Perhaps the best examples of the most intense action of the gabbro are the inclusions of slate, large and small, that occur abundantly in the gabbro outcrops near the Rove outcrops. These and the inclusions of diabase sills have been so recrystallized that the two kinds of inclusion are almost indistinguishable, except where the slate retains a little bedding or the diabase has some corroded phenocrysts. In a few places the two rocks have been identified and traced into the metamorphic zone.

[22] R. A. Daly, "Bushveld Igneous Complex of the Transvaal," *Bulletin of the Geological Society of America,* 39:746–750 (1928); P. A. Wagner, "Explanation of Sheet 17," Geological Survey of South Africa, p. 45, 48; and T. T. Quirke in *Bulletin of the Geological Society of America,* 38:753 (1927).

A dike crossed by the portage from Mayhew Lake to Birch Lake was noted on page 8. A mixed series near the gabbro is also well exposed in Secs. 8, 9, and 3, T. 64 N., R. 2 E. This location can be reached most easily by canoe a few miles from the resort at McFarland Lake. A mass of gabbro transgresses across two belts of slate and two of diabase, so they can all be traced up into the metamorphic zone. Both the rocks become sugary brown hornfels.

TABLE 6. — COMPARISON OF ANALYSIS OF HORNFELS WITH THOSE OF THE ORIGINAL SLATE AND GRAYWACKE

	1	2	3
SiO_2	82.15	64.77	57.77
Al_2O_3	5.38	14.45	18.52
Fe_2O_3	1.47	1.84	5.23
FeO	1.08	4.54	2.52
MgO	2.22	2.34	2.72
CaO	1.85	2.33	3.11
Na_2O	1.84	1.37	2.48
K_2O	1.09	5.03	4.11
H_2O+	.74	1.92	2.11
H_2O-	.07	.07	.15
CO_2	...	.41	...
TiO_2	.35	.60	.89
P_2O_5	...	.20	...
SO_3	...	.60	...
MnO	...	.11	...
Total	98.23	100.58	99.61

1. Graywacke from the east line of Sec. 33, T. 65 N., R. 3 W., close south of Loon Lake. D. M. Davidson, analyst.
2. Slate from the bed of the Cross River where it flows into Gunflint Lake, Sec. 24, T. 65 N., R. 4 W. C. M. Chatard, analyst.
3. Hornfels from a sandy phase of the Rove formation, altered by gabbro, SE¼ Sec. 36, T. 65 N., R. 2 W., on the south shore of Birch Lake. D. M. Davidson, analyst.

Other examples of strong contact action on slate may be seen along the portage and creek from Crocodile Lake to Bearskin Lake and in a bluff south of the west end of Loon Lake.

In many places — for example, one-fourth mile east of Loon Lake on the Gunflint trail — there is a confused breccia of hornfels fragments for a few feet from the gabbro in a matrix of mixed hornfels and aplitic and pegmatitic emanations and gabbro. A few show graphic intergrowths of quartz and feldspar in the midst of the more ordinary hornfels, probably where certain beds were rich in quartz. Intergrowths of ferromagnesian minerals are mostly "wormy," like the reaction rims in the gabbro.

The minerals of the slate hornfels are largely the same as those of the slate — quartz, biotite, graphite, chlorite, feldspar, pyrite, magnetite, hornblende, and sericite. Close to the gabbro are pyroxenes (both augite and hypersthene) and olivine, and the feldspars (mostly andesine) become fresher, whereas sericite largely disappears. Magnetite is notably more abundant but is not a result of additions of iron, but rather of a change of oxidation or equilibrium. Some cordierite is locally abundant but it does not occur in the "ghosts," or metacrysts, which are characteristic of the contact rocks of the sills. Apatite, titanite, and zircon appear as common accessories. Some sericite and other hydrothermal alterations of the metamorphic minerals are obscure aggregates. Kaolinite is formed in the weathering of the feldspars.

The graywackes with abundant quartz have recrystallized in much the same way as slates, but the quartz has modified the texture by forming euhedral or embayed quartzes or graphic intergrowths with feldspars.

Davidson,[23] who had made a study of the compositions of the sediments, for purposes of comparison made an analysis of hornfels, the sedimentary origin of which is clearly shown by its stratification and position in the outcrop. It seems very probable from his data that some material has been added as igneous emanations for at least a few feet from the gabbro contact. The silica has been reduced and the lime increased, as is common in a number of contact rocks near gabbro in other parts of the world.[24]

[23] D. M. Davidson, "The Animikie Slate of Northeastern Minnesota" (unpublished master's thesis, University of Minnesota, 1926).

[24] H. H. Read, "Petrology of the Arnage District," *Quarterly Journal of the Geological Society of London,* 79:483–484 (1923).

THE LOGAN SILLS AND RELATED INTRUSIVES

General Description

The Logan sills stand out as the most prominent topographic features of the region. The high ridges and especially the northward-facing bluffs are for the most part made of intrusive diabase. (See Figures 25 and 26.) Easily accessible exposures occur on the south side of Gunflint, Loon, West Bearskin, Clearwater, and McFarland lakes. Nearly

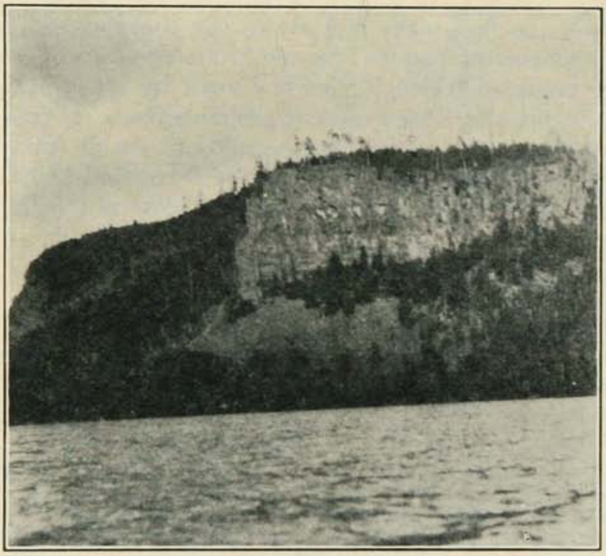


Figure 25. — Northward-facing diabase bluff with talus slope covering most of slate beneath. South shore of Clearwater Lake, T. 65 N., R. 1 E.

all the boundary lakes have a bluff of diabase on the south side of the lakes. Many bluffs contain several sills that alternate with slate and for the most part have a thick sill at the crest.

Near Grand Portage and from that locality north and east to Pigeon Point, dikes seem to be more common than sills, but both dikes and sills traverse the Rove formation from end to end of the Minnesota area.[1] The dikes form ridges that are just as conspicuous as the sawtooth mountains formed by sills, but the dike ridges are different in that they commonly have a bluff on both sides. Vertical contacts with metamorphic effects are well exposed in many places.

[1] The dike forming Mount Josephine runs across the point to High Falls of Pigeon River; it does not branch to Pigeon Point, as was once suggested (United States Geological Survey Bulletin 109, p. 16), but it perhaps feeds the sill.

It is not at all certain why dikes are more abundant in one area than in another, but there are several differences in surroundings that might influence the form of intrusive. First, the more abundant sills are in slates, while the more abundant dikes are in the graywackes and quartzites, more massive, jointed rocks. Secondly, the sills are closer to the Duluth gabbro than to the dikes. Thirdly, analogy with other districts might suggest that there was a center of eruptive activity near Grand Portage and that the sills formed, as is common, at a slightly greater distance from the center; the dikes here, however, have only an ill-defined suggestion of radiation from a center. Finally, it may be noted that the sills occur at a lower horizon than the dikes and may have been at greater depths at the time of intrusion.

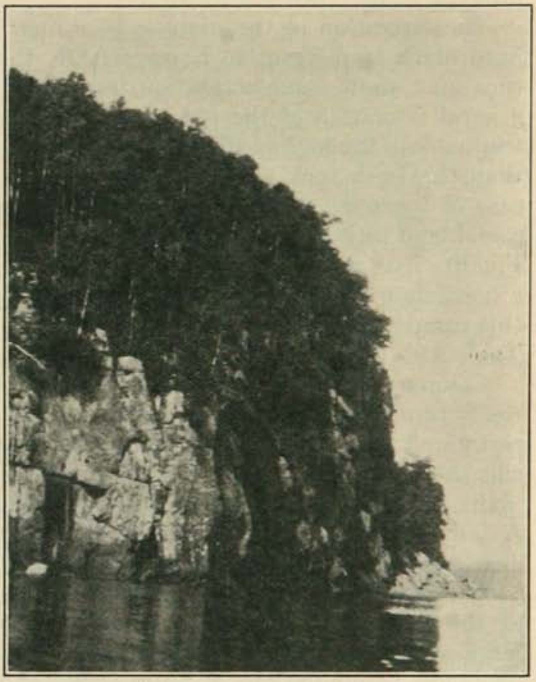


FIGURE 26. — Diabase cliff on north side of Pigeon Point.

The relationship between the dikes and sills is clearly indicated by their association, by their perfect similarity in composition and slight degree of alteration, by a belt of diabase dikes merging into a belt of diabase sills, as shown by field maps, and finally by actual exposures of sills that transgress the bedding of the slate in the floor after having followed the beds a long distance. Such a transgressing sill is exposed south of the outlet of John Lake, and several others are known. (See Figure 11.)

Similar dikes and sills occur in the underlying basement complex,[2] in the Gunflint iron-bearing beds, and in the overlying Keweenawan flows. On the bluff near the outlet of South Fowl Lake a dense basic dike cuts the large sill of the ridge. This was not observed elsewhere, but later dikes are known to cut the Duluth gabbro. At least two large dikes pass from the area of Rove formation southwest into the Keweenawan rocks. (See Plates 12 and 13.)

On Pigeon Point and possibly elsewhere the sills contain a few fragments of the overlying sediments, which suggests that the intrusive

[2] Gill, *op. cit.*

forces or the heat must have been severe enough to stope down fragments from the roof.

The sills vary from a few feet to more than 500 feet in thickness. Even a single series of outcrops, such as indicates a continuous sill, may show a greater thickness of diabase at some points than others. Many of the smaller sills may have been missed in the field work, because the larger sills cause prominent ridges and their talus slopes conceal not only the underlying slate but any small hard sills that may be intruded into the slate. (See Figure 25.)

The alteration of the diabase is ordinarily not very important. The hard black trap seems to be very fresh, though a microscopic examination may show some alteration, especially of the olivine, and a more general alteration of the phases grading toward red granite. The black trap rock in the high bluffs weathers brown or gray and somewhat lighter than the fresh rock as the glassy feldspars turn to white kaolinite. In case of thorough recent weathering some exposures have become spheroidal, and ultimately the diabase forms a rough, brownish, gravelly soil. Finally, it is noteworthy that the gabbro recrystallizes the sill rocks to a hornfels with fresh minerals such as might form in an igneous rock of this composition, but with a sugary hornfels texture.[3] (See Analysis 4 in Table 8.)

Columnar jointing is seen in some sills and small dikes but is not really prominent or regular. A sheeting in the direction of the sill and a rectangular jointing through it are as common as the columns. In most sills the major joints run down the dip and along the strike. The coarser diabases have a somewhat oily luster caused by the presence of olivine. A few of the diabases are decidedly magnetic, but magnetism is not characteristic of the intrusives as a whole.

The texture of the sills and dikes varies from glassy and spherulitic at the borders of the small masses to granitoid in the centers of the large ones. Near the top of the medium and large sills and in some large dikes are accumulations of phenocrysts of plagioclase up to 6 inches in length. These have considerable theoretical significance as suggesting the method of formation of anorthosite. Some were noted in a diabase on one side of Loon Lake by N. H. Winchell many years ago, and a large number have been seen in the more recent survey. In several cases they are oriented in the plane of the sill or parallel to the dip of the sediments. The phenocrysts are commonly aggregated into masses of light color and coarse texture, and some of these aggregates are in turn intruded by the diabase, in which they seem to have grown. The feldspar masses become fragmental.

The columnar jointing in the tops of sills and walls of dikes seems to have formed very early in the cooling of the masses, and wherever shrinkage cracks opened up before the main magma was solid, the joint cracks were in a position to receive pegmatitic emanations as a network

[3] Bayley, *op. cit.*, p. 38–42, gives several further details of occasional alterations.

of dikelets. The chilled margins resist erosion very well, and the polygonal network of dikelets is a striking feature of many outcrops. The plane of the eroded surface generally coincides with the top of the sill, and this shows the angle of dip of the series better than any other feature.

Not only are the main portions of the sills and dikes megascopically crystalline but the fabric is diabasic in nearly all of them. Where plagioclase and augite are abundant as usual the rock is properly a diabase. Probably 80 per cent of all the intrusives are diabase, and of these only about 10 per cent have phenocrysts. Labradorite makes up about 60 per cent of the diabases. As quartz, silicic feldspars, and other minerals increase, the texture is modified, through granophyr diabases to granitoid rocks.

Bayley in describing the diabases of Pigeon Point separates the description of the dike rocks from that of the sills, noting that some of the dikes have biotite and others have no mica, and that the dike rocks are more altered than the sills.[4] In the larger region here covered the contrast is not so clear. The dikes and sills have a similar degree and kind of alteration and variation, and the texture ranges from glassy to highly porphyritic, diabasic, and granitoid in both forms of occurrence.[5] None of the sills except that on Pigeon Point is as coarse as most of the Duluth gabbro.

The minerals of the sills (and dikes) are in order of importance, basic labradorite, augite, magnetite, ilmenite, olivine, silicic feldspars, quartz, biotite, and hornblende, both brown and green. There are accessory apatite, sulphides, zircon, and secondary chlorite, uralite, serpentine, talc, epidote, sericite, hematite, kaolinite, leucoxene, rutile, and carbonate. The feldspathic phases may have zeolite. Some hypersthene has been noted, but most if not all of it has been in the rocks altered by gabbro intrusion.

The labradorite is commonly uniform in euhedral crystals in both the porphyries and the diabase. The labradorite associated with granophyr shows a gradation to a more silicic outer zone.

The specific gravity of the plagioclase phenocrysts was found to be 2.717, and that of the feldspars in the groundmass ranged from 2.699 to 2.717. An analysis of the feldspar of a fresh diabase is given in Table 7. The red feldspar of the silicic phases had a specific gravity of about 2.577, while that of the silicic plagioclase aggregates was from 2.61 to 2.65. In the intermediate rock the plagioclase had a specific gravity of 2.65 and the red feldspar of 2.583±. An analysis of the red feldspar is given in Table 7.

Augite varies from colorless to pink and purple. It is rarely euhedral but almost always encloses the labradorite in an ophitic or diabasic

[4] *Ibid.*, p. 44–48.

[5] Bayley discusses former usages of the term diabase and refers to the coarse olivine rock as gabbro. It is here included with diabases wherever plagioclase needles formed before augite, whether coarse, medium-grained, or fine-grained.

fabric. The composition of the augite was tested and found to be that of a pigeonite. (See Table 7, column 3.) Possibly two varieties are present. Twinning and the structure of a "herringbone" are seen in a few cases, and the parting characteristic of diallage is noteworthy in the pyroxene of several sills.

TABLE 7.—ANALYSES OF FELDSPAR AND DIALLAGE OF THE INTRUSIVES

	1	2	3
SiO_2	53.73	65.00	48.34
Al_2O_3	30.39	18.22	2.90
Fe_2O_3	1.26	2.64	4.68
FeO			14.15
MgO	...	.06	11.34
CaO	10.84	1.06	15.10
Na_2O	3.76*	8.40	...
K_2O	...	4.18	...
Ignition	...	.46	...
TiO_2	...	...	1.98
Total	100.00	100.02	98.49
Sp. Gr.	2.699	2.577	....

* By difference. Correctly quoted; probably should be 3.78.

1. Fresh plagioclase at Pigeon Point separated from diabase by Thoulet solution. Bayley, *op. cit.*, p. 34.
2. Red feldspar from fresh red rock (granite) at Pigeon Point. *Ibid.*, p. 52. J. E. Whitfield, analyst.
3. Diallage from fine fresh diabase at Pigeon Point. *Ibid.*, p. 36, R. B. Riggs, analyst. See also A. N. Winchell, *Elements of Optical Mineralogy* (New York, 1927), Part 2, p. 181, where this variety is called pigeonite.

All the iron ores present are probably intergrowths of magnetite and ilmenite, many having been partly altered to leucoxene. Skeleton forms in the fine-grained rocks indicate that some magnetite grew rapidly and apparently early; but in the coarser rocks some magnetite is later than labradorite, filling the interstices just as augite files interstices in diabase. Numerous needles and rods in the coarse rocks suggest the forms of ilmenite. The biotite occurs chiefly along the edges of the ore minerals, and some grains have pleochroic haloes.

The silicic feldspars intergrown with some of the quartz are probably of several kinds, though they perhaps grade from one to another. They are commonly red from dusty hematite and are much kaolinized. The silicic feldspar that formed in continuity with zoned plagioclase is no doubt plagioclase, but is probably a potash-bearing oligoclase. Both albite and orthoclase are apparently contained in those phases of sills that are rich in red feldspar.

About 100 specimens were collected to illustrate the intrusives of the district. Nearly half of these contain olivine and most of the rest contain quartz. Several contain neither quartz nor olivine. In four or five large coarse-grained masses both olivine and graphic intergrowths of quartz and acid feldspar grew together. These odd combinations of a mineral consisting of silica with an olivine that is "unsaturated" with silica may be illustrated by the rock of the sill at the tip end of Pigeon Point and the rock of the dike of Mount Josephine, 500 feet above Lake Superior. Examples of quartz in olivine rocks are known in other parts of the world,[6] but ordinarily these show more corrosion and resorption of the olivine than is evident here. The olivine in these rocks is not wholly fresh in any case, but it is not greatly altered in the unweathered coarse to medium diabase. Much of it is rounded as if formed early and attacked by magmatic corrosion, but some, which fills angular spaces between plagioclase needles, is late to crystallize.

Analyses of the several igneous rocks of the Logan intrusives are given in Table 8.

TABLE 8. — ANALYSES OF THE LOGAN INTRUSIVES

	1	2	3	4	5	6
SiO_2	50.04	49.88	51.00	48.46	49.42	47.78
Al_2O_3	11.70	18.55	18.93	19.04	....	....
Fe_2O_3	2.28	2.06	1.19	5.67	17.29	17.03
FeO	13.51	8.37	9.54	7.44		
MgO	4.20	5.77	4.04	5.21	....	....
CaO	7.16	9.70	9.46	8.56	....	....
Na_2O	3.47	2.59	1.46	.69	....	....
K_2O	1.03	.68	1.20	1.24	....	....
H_2O+	1.28	1.04	1.18	1.40	....	....
H_2O-	.07	....	.16	.44	....	....
CO_2	.25	....	....	....	....	....
TiO_2	3.76	1.19	1.82	1.60	....	....
ZrO_2	None	....	....	....	....	....
P_2O_5	.47	.16	....	.04	....	....
S	.11	....	.02	....	....	....
Cr_2O_3	None	....	....	....	....	....
MnO	.15	.09	....	....	....	....
BaO	.02	.02	.15	....	....	....
Cl	.10	....	....	....	....	....
Total	99.60	100.20	100.15	99.79	....	....

1. Diabase from a chilled phase near the top of a sill in Sec. 25, T. 65 N., R. 2 W. Average diabase. R. B. Ellestad, analyst.
2. Composite sample of five fresh specimens of olivine diabase from Pigeon Point. W. F. Hillebrand, analyst. United States Geological Survey Bulletin 109, p. 37. Specific gravity 2.923–2.970.
3. Relatively fresh, coarse quartz diabase from SW¼ NW¼ Sec. 35, T. 65 N., R. 2 W. H. F. Kendall, analyst.
4. Hornfels derived from a diabase, probably of the same age as the sills in the Rove formation; from the East Mesabi district, Sec. 35, T. 61 N., R. 12 W. George Ward, analyst.
5. Diabase from a sill at the west end of Gunflint Lake. Partial analysis by George Ward.
6. Diabase from the northwest corner of Dunn Lake, Sec. 25, T. 65 N., R. 2 W. Partial analysis by George Ward.

[6] J. S. Diller, *A Late Volcanic Eruption in Northern California* (United States Geological Survey Bulletin 79, 1891), p. 21–33.

Segregations and Differentiation

As noted above, numerous labradorite phenocrysts and masses of anorthosite occur in certain diabases. These are characteristic of the upper parts of sills 20 or more feet thick throughout the Rove slate area and beyond that in the corresponding Virginia slate area of the Mesabi Range, a distance of more than 100 miles. Good examples of both phenocrysts and segregated anorthosite may be seen on the north shore of Loon Lake and north of Pine Lake.

Sills like these are numerous, and the relations in them strongly suggest that these aggregates of feldspar were formed by clustering of phenocrysts. This cumulative evidence, the result of several years of work, has been needed to settle the matter in the minds of the geologists of the Minnesota survey. In the earlier stages of the work it was thought probable that the many fragments of anorthosite found in diabase had been derived from some large mass of anorthosite in another formation, such as the Duluth gabbro. This may still be considered possible, because it is very certain that the present form of many anorthosite masses is a result of breaking rather than of growth. As the work continued, however, it was found that some of the sills seem to have been intruded through thousands of feet of sediments that are exposed only a short distance away and that contain no anorthositic phases of older rocks that could have furnished such xenoliths. Furthermore, some of the masses of anorthosite are so large that they could hardly have been carried up as xenoliths from a deeper source through such dikes as those seen in this region. These masses at least seem to have grown in the chambers where they are now found. If some of the masses were formed where they are found, probably all of them were so formed, and their fragmental appearance may be attributed to disturbances that occurred during a late stage of the solidification of the magma.[7]

The best of these segregations occur in rather large sills and suggest that the still larger sills should supply even more material for such accumulations. The largest sill in the district is that at Pigeon Point; and while it should have had a similar history, it has long been known that this mass is complicated with a conspicuous red granite phase, while the anorthosite is more obscure.

Considerable anorthosite is found, however, at or near the top of the sill along the south shore of the point; for example, from 100 to 200 yards east of Little Portage Bay, and in places farther east. No anorthosite nor even any highly porphyritic gabbro is found below the main granite differentiate of the sill. The plagioclase seems to have floated up in this sill, as in many others, at an early stage.

Related to the diabase sills and dikes and in close association with them are a group of dikes and sills of "red rocks" and intermediate rocks, most of which are small in comparison with the diabase. Grada-

[7] F. F. Grout, "Anorthosite and Granite on Pigeon Point," *Bulletin of the Geological Society of America,* 39:562–563 (1928).

tions are found from diabase to rocks of granitic composition under several conditions. In Sec. 35, T. 64 N., R. 5 E., a black diabase grades to red quartz porphyry in the space of about 12 inches; and while there can be little doubt that both are igneous, the groundmass of the quartz porphyry is of a peculiar granular texture, rich in quartz, and its phenocrysts are not euhedral. Gradations on a grander scale are exposed on Pigeon Point (see below, page 48) and the islands northeast of it, where the origin of the red rock has been a subject of much discussion.

In contrast to these there are a number of separate intrusive masses of red rock (granite) of a character that cannot be distinguished from the red rock that grades into diabase. There are dikes of red porphyry cutting diabase and slate in the hill at 500 paces east of the southwest corner of Sec. 26, T. 64 N., R. 6 E., and sill-like masses of red granite on the east side of Wauswaugoning Bay and the islands south of Pigeon Point. The sills that have a red granite phase have it chiefly at or near the tops of the sills; and the independent red rock (granite) bodies may be apophyses from some such magmas.

The red rock (granite) has been described by Bayley.[8] The color is brick red, some of the feldspar being pink and some a darker red. There are scattered specks of a green chloritic mineral after biotite on the weathered red surfaces. Many exposures show drusy or miarolitic cavities, or spots that seem to have been cavities, now filled with a carbonate. The texture of most of the rock is granitoid with much graphic intergrowth, but some of the late magma probably moved out against some cold rocks and became a porphyry with corroded quartz and zoned feldspars in a groundmass of graphic and crude spherulitic intergrowths. A mineral separation gave Dr. Bayley 62.75 per cent feldspars of two kinds, 34.93 per cent quartz, and 2.30 per cent chlorite, biotite, etc. Most feldspars have a twinned center and a graphic outer zone, and some are slightly altered to calcite. They are dusty in the outer red zones with kaolin and hematite. (See Table 7.) Pleochroic haloes occur in the chlorite and biotite. The rocks range from quartz keratophyr to sodic granite. Most of them may be classed as granophyrs.

Exceptionally large hornblende crystals, up to an inch or more long and partly in groups or clusters, are found in several places in the intermediate rocks that show both gray and pink feldspars in the field. The matrix around them, however, is of normal grain.

Between the olivine diabase and the quartz diabase the rocks have commonly neither quartz nor olivine; but, as noted above, some large masses have both minerals.

Certain features of the gradation from diabase to red rock (granite) are noteworthy. As the diabase comes to have less and less olivine and begins to have quartz in graphic intergrowths, there is a notable abundance of apatite and biotite, which occur in much smaller quantity in the normal olivine diabase. An analysis of intermediate rock is given in

[8] *Op. cit.*, p. 49–59.

Table 9. These rocks are not as silicic as common granite, but some are rich in granophyr.

The evidence of the thin sections is clear that a series of diabases exists, varying from those rich in olivine to those rich in quartz and silicic feldspar. The series seems to be complete and to be independent of the presence of quartz rocks near by. While there was no doubt some assimilation of sediments by the magma, there is quite conclusive evidence that the series from olivine diabase to granite would have differentiated from the original magma even if the wall rocks had been diabase.

This series, as well as the series from diabase to anorthosite, is thus attributed to differentiation. The large sill on Pigeon Point, the classic example of these series, is given detailed discussion below.

Assimilation and Related Processes

Several of these red granites occur close to the contacts of a large diabase mass and some highly siliceous sediment, and it has been suggested that the more siliceous phases of the igneous rock are in some way related to the siliceous sediment. The several suggestions as to this relationship are (1) that the red rocks are products of fusion of sediments; (2) that they represent ultrametamorphism of the sediments; and (3) that they represent the product of solution of the sediments in the diabase and its later differentiation. The discussion has centered around the Pigeon Point rocks containing graphic intergrowths. It may be noted here that graphic intergrowths seem to have formed by recrystallization and contact action outside the magma and that they resemble most remarkably those graphic intergrowths that form at a late stage inside the igneous rocks. This is not necessarily a sign of genetic relation.

Pigeon Point Sill

Bayley gives the following description of Pigeon Point and the surrounding region:

> Pigeon Point is the name given to the northeastern portion of Minnesota, embraced within sections 25, 26, 27, 28, 29, 30, 31, and 32, T. 64 N., R. 7 E. of the fourth principal meridian. It extends from the main shore N. 77° E., into Lake Superior (Pl. III). Pigeon river and Pigeon bay separate it from Canada on the north; on the south side it is washed by Lake Superior, and on the west side by the waters of Wauswaugoning bay. Measured from the eastern side of Wauswaugoning bay to its easternmost extremity it is 5½ miles in length. Its width varies from a few hundred feet to as much as 1 mile in its western part, its average width being somewhere between a quarter and a half mile.
>
> It is isolated from the mainland by a stretch of low swampy country, which runs from Wauswaugoning bay northeasterly to Pigeon river. The traces of former coast lines in the interior show that the swamp was at some earlier time covered with water, and that the point was consequently an island, or, rather, a group of islands, since all the lowlands on the point contain the remains of raised beaches.
>
> One of these areas of lowland, formerly a strait, but now an isthmus, is situated about a mile and a half from the eastern end of the point. It is a narrow shingle beach, about 200 feet wide, over which the Indians are accustomed to portage in order to avoid the large stretch of open water at the mouth of Pigeon bay, and to which they have given the name of "Little Portage." This isthmus affords a convenient means of dividing the point (for purposes of description only) into an eastern and a western portion.[9]

[9] Bayley, *op. cit.*, p. 15.

Pigeon Point is made up of Animikie sedimentary rocks and an intrusive sill about 500 feet thick. This sill is composed of a series of different rocks that have been so fully exposed by glaciation and wave erosion as to show clearly the relations between the members of the series. The sedimentary rocks above and below the sill are chiefly gray to black quartzite and slate, and the overlying strata are altered to red contact rocks. In some places near the intrusive rock this contact rock contains some micrographic intergrowths of quartz and red feldspar that greatly resemble those in the red silicic phase of the intrusive. Nearly all this alteration appears to have occurred in the overlying strata; the few exposures of the floor show relatively little contact metamorphism, but even in these some rock shows a little graphic intergrowth.

GENERAL FEATURES OF THE SILL

The main intrusive body on Pigeon Point is a sill that in places cuts across heavy beds of the Animikie quartzite into which it is intruded. Daly[10] has summarized very convincingly the evidence, both structural and petrographic, that the intrusive mass is a sill; and Bayley early noted[11] several features that left the subject at least an open question. For example, he speaks of it as "plutonic"; as being "intruded between strata"; and as having feldspars oriented parallel to the sedimentary

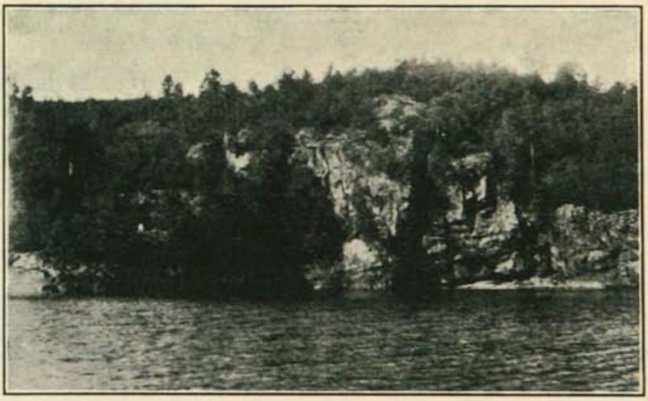


FIGURE 27. — Diabase sill over dipping quartzite. Shore of Pigeon Bay near mouth of Pigeon River.

beds. Several outcrops, some mentioned by Daly, show the concordance of the upper part of the sill with the bedding of the quartzite. (See Figure 28.) A particularly good exposure occurs south of the small area of gabbro about a mile east of Marks Bay, and there are several others along the shore east of Little Portage Bay.

The discordance of the sill contacts, however, is in places conspicuous. Aside from the blocky re-entrants of granite in the roof, the variable

[10] Daly, *op. cit.*, p. 426–430.
[11] Bayley, *op. cit.*, p. 23, 109, 115.

width of the outcrop of the sill strongly suggests discordance. The sedimentary beds and the structural lines of the intrusive mass dip south at an angle of about 15°, and the width of the exposure of the intrusive rock ranges from less than a quarter of a mile on the west side of Little Portage Bay to almost half a mile near the mouth of Pigeon River. The sill must vary greatly; in some places it is probably not over 250 feet, while in others it may be as much as 700 feet thick.

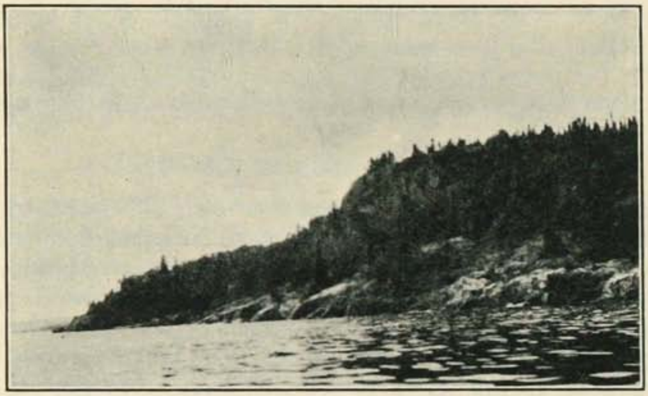


FIGURE 28. — Dip slope on south side of Pigeon Point. The bluff is rhyolite porphyry.

This great sill was first encountered at its west end, on Wauswaugoning Bay, and its outcrops are so numerous from that locality to Pigeon Point, over 6 miles east, that its continuity for that distance can hardly be questioned.[12] Daly presents the evidence that the several rocks of the sill are an intrusive unit rather than the products of a succession of intrusions.[13]

COMPONENTS OF THE SILL AND THEIR RELATIONS

From the roof of the sill down, the following rocks have been noted:

1. Chilled diabase containing in some places abundant phenocrysts of labradorite and small masses of anorthosite
2. Red rock (granite)
3. Intermediate rock
4. A large volume of diabase gabbro
5. Chilled diabase (near the floor)

The petrography of most of these rocks has been described by Bay-

[12] Bayley's map of the sill (his Plates XIV–XV) was made in part by interpolation, and he evidently missed some outcrops in a wooded swamp west of the area shown on Figure 1 in the present monograph. The area of numerous outcrops along the shore is confused by minor intrusions, but there is probably no such offset or fault as one might suppose from Bayley's map. (See Daly's paper, page 430, footnote.)

[13] Daly, *op. cit.*, p. 434.

ley,[14] and details that seem to have no important bearing on the problem of the origin of the rocks need not be considered here.

1. The chilled upper phase of the sill consists largely of diabase gabbro, of medium grain, in which the feldspar is labradorite. In some places there are abundant phenocrysts of labradorite, the largest several inches long, and the diabase gabbro grades into anorthositic gabbro. There are also small "bouldery" masses of coarse-grained true anorthosite. This upper phase is not continuous in outcrop. In the western part of the area mapped (see Figure 29) it forms a definite belt, but toward the east, where the exposures have been most thoroughly studied, the belt is broken by intrusives of later phases of the magma.

FIGURE 29. — North-south section across Pigeon Point. The locality is about half a mile east of the mouth of Pigeon River. The diagram shows the supposed relations of the phases of the sill.

Q. Animikian quartzite and slate; 1, chilled basal gabbro; 2, gabbro; 3, intermediate rock; 4, granite; 5, chilled upper gabbro with anorthosite segregations.

2. Beneath the diabase is a zone of "red rock" of variable thickness. This rock is a sodic granite that shows considerable variation in texture from place to place, and most of it contains abundant micrographic intergrowths, making the rock a granophyr. It intrudes the upper chilled gabbro and anorthosite with fairly sharp contacts and with some signs of assimilation. In places it rises through the roof and includes fragments of sedimentary rock. It is abundant at Little Portage Bay and in a belt west of that bay but is less common farther east, where it cuts the diabase and the quartzite.

3. The granite grades downward through a narrow zone of "intermediate rock" into the large body of diabase gabbro of the sill. The intermediate rock as here mapped includes material ranging in composition between two extremes; a rock containing only red silicic feldspar and a rock containing gray labradorite. Any rock containing two feldspars, one red and the other gray, has been mapped as intermediate. Even with this wide range, however, there is less intermediate rock than granite. The largest areas of this phase are east of Little Portage Bay. Daly reduced the intermediate rock area still more, apparently by including with the gabbros some rock that contained a small amount of red feldspar.

4. Below the intermediate rock is the main diabase gabbro of the sill, in which the feldspar is labradorite, though rarely in large pheno-

[14] *Op. cit.*, p. 32–113.

crysts. Much of the diabase gabbro contains olivine, which, however, is not so concentrated as to form a peridotite in any layer. Probably the sill is not large enough to have developed such a segregation. The transition of the diabase gabbro to the intermediate rock no doubt involves an increase in silica, so that parts of the rock are free of olivine, but these parts are not distinguished in the mapping.

5. In a few places where the floor of the sill is exposed, the diabase near the contact is slightly finer grained than the main body of the gabbro.

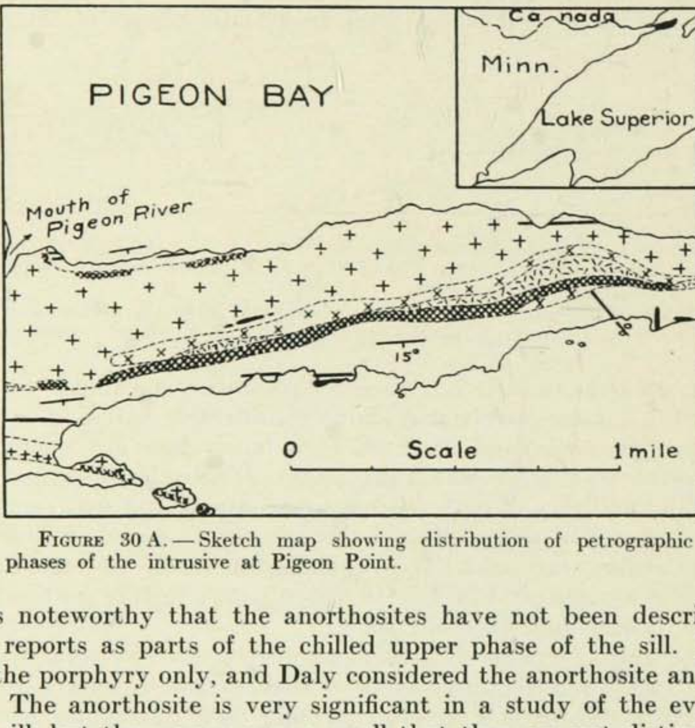


FIGURE 30 A. — Sketch map showing distribution of petrographic phases of the intrusive at Pigeon Point.

It is noteworthy that the anorthosites have not been described in earlier reports as parts of the chilled upper phase of the sill. Bayley noted the porphyry only, and Daly considered the anorthosite an earlier dike.[15] The anorthosite is very significant in a study of the evolution of the sill, but the masses are so small that they are not distinguished on the map from the rest of the upper chilled diabase.

The compositions of some of the rocks are shown in Table 9 on the following page.

Fragments of sedimentary rock occur in the granite, the intermediate rock, and the gabbro, but none have been found in the anorthosite nor in the highly porphyritic gabbro. These fragments, being of low specific gravity, would not settle deep into the gabbro magma; few are found except near its top.

Few contacts of the granite and the intermediate rock with the overlying quartzite have been observed. A diabase intervenes between these

[15] Bayley, *op. cit.*; Daly, *op. cit.*

silicic differentiates and the roof of the sill. Contacts are exposed in many places in the western part of Pigeon Point and also in places in the eastern part. In only a few places has the granite or the intermediate rock stoped or dissolved the early roof phase of the magma so as to underlie the quartzite directly. Contacts of these phases are much less common and less well exposed than the earlier maps of the area might suggest, but they are numerous enough to show that the granite and the intermediate rock intrude and include fragments of the quartzite.

If the granite is all of the same age, it seems to be the latest igneous rock of the sill, for it cuts gabbro, anorthosite, intermediate rock, and

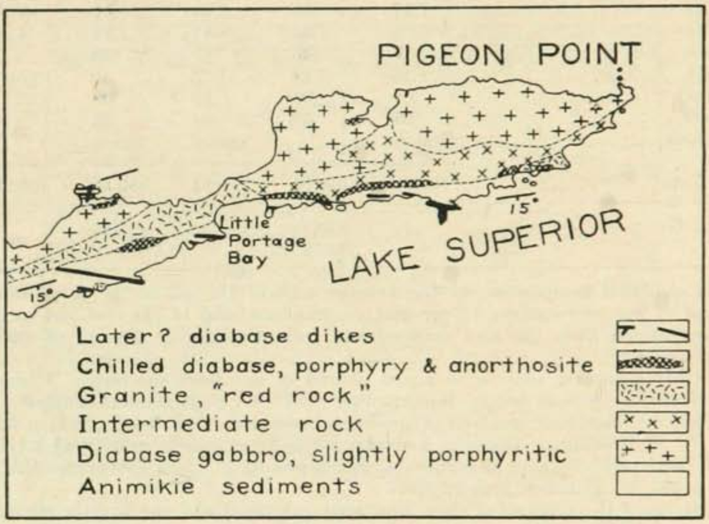


FIGURE 30 B. — Sketch map showing distribution of petrographic phases of the intrusive at Pigeon Point.

the roof and floor of the sill. The red stringers seem to be apophyses from the sill, but they are so short and so discontinuous in outcrop that Bayley was uncertain of their relations. Daly[16] makes the valuable suggestion that some granite escaped from the magma under "gas tension," so that some may have formed at an earlier stage of magmatic action than the final granite stage; yet all seem to be related to the main intrusive. No later dikes were seen to cut the granite, though some conspicuous dikes of black diabase cut the sediments and the gabbro. These dikes seem to have no significant bearing on the problem of the origin of the main rocks in the sill; they are therefore given no further consideration here.

Intermediate rock in somewhat ill-defined dikes cuts the main gabbro and the upper roof phase of the diabase, including the highly porphyritic and anorthositic phases.

[16] *Op. cit.*, p. 43.

TABLE 9. — ANALYSES OF ROCKS IN SILL AT PIGEON POINT, MINNESOTA

	1 Total Sill	2 Gabbro	3 Intermediate Rock	4 Red Rock (Granite)	5 Average Sediment
SiO_2	53.48	49.88	57.98	72.42	70.31
Al_2O_3	17.31	18.55	13.58	13.04	12.81
Fe_2O_3	2.00	2.06	3.11	.68	7.26
FeO	7.68	8.37	8.68	2.49	.88
MgO	4.80	5.77	2.87	.58	2.03
CaO	7.72	9.70	2.01	.66	.60
Na_2O	2.82	2.59	3.56	3.44	2.19
K_2O	1.57	.68	3.44	4.97	1.90
H_2O+	1.23	1.04	2.47	1.21	2.22
P_2O_5	.19	.16	.29	.20	...
TiO_2	1.16	1.19	1.75	.40	trace
MnO	.09	.09	.13	.09	...
BaO	.04	.02	.04	.15	...
Others	traces	...	traces	traces	...
Total	100.09	100.20	99.91	100.33	100.20
Sp. Gr.	...	2.923–2.970	...	2.620	...

1. Calculated composition of the average rock of the sill in the proportion of 77 per cent gabbro, 11 per cent intermediate, and 12 per cent red rock, estimated from the area mapped and from the specific gravity of each rock.
2. Olivine gabbro; analysis of mixed powder of five fresh specimens. United States Geological Survey Bulletin 109, p. 37. W. F. Hillebrand, analyst.
3. Intermediate rock; analysis of specimens from near "red rock." *Ibid.*, p. 63. W. F. Hillebrand, analyst. A similar rock had a specific gravity of 2.741.
4. "Red rock" (granite), analysis of mixed powder of seven specimens. *Ibid.*, p. 56. W. F. Hillebrand, analyst.
5. Mean of the analyses of three unaltered quartzites and one slightly altered slate. *Ibid.*, p. 113.

TABLE 10. — ALKALI CONTENT OF "RED ROCK" (GRANITE) SHELL AROUND INCLUSIONS AND ASSOCIATED ROCKS

	Intermediate Rock	Red Rock (Granite)	Quartzite
Na_2O	2.32	2.78+	2.03
K_2O	1.17	5.22+	1.57

The relative ages of the anorthosite and the diabase gabbro are inferred by analogy from the relations shown in the less differentiated sills in the same formation farther west.

Calculation and comparison show that the total sill, like the smaller sills farther west, has a composition not far from that of average diabase, gabbro, or basalt. If such a magma had been cooled more rapidly no granite would have been formed.

The conclusion follows that the anorthosite in this sill was formed in place; that it was formed as in some smaller sills, by the upward movement and aggregation of crystals of labradorite; and that it was

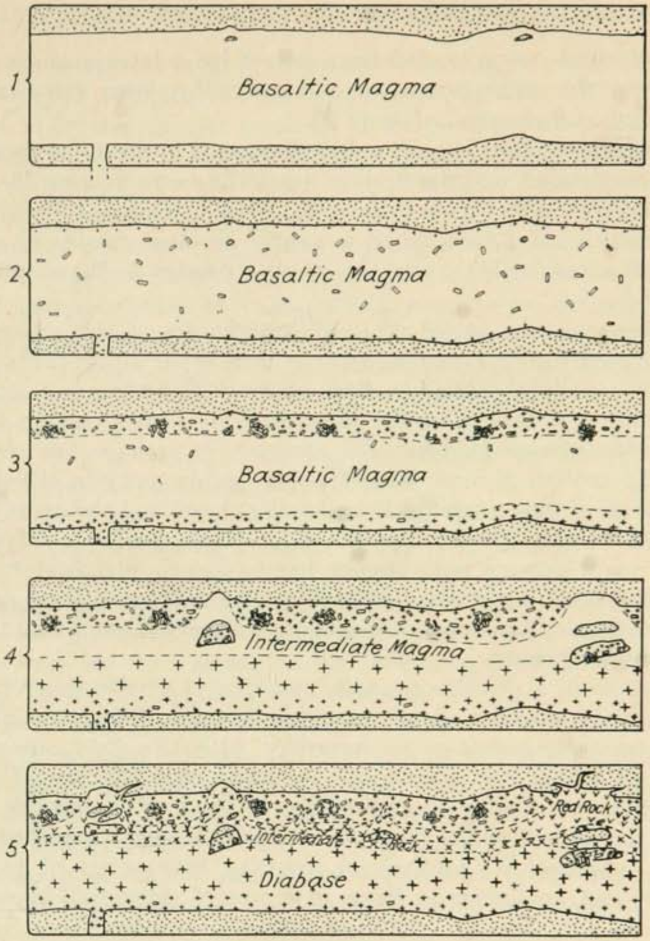


FIGURE 31. — Stages of development of sill at Pigeon Point.

1. Intrusion, generally conformable; slight shattering.

2. Phenocrysts develop as the top and bottom are chilled to diabase. Possibly some fragments of quartzite are dissolved.

3. Phenocrysts rise and some are segregated to form anorthosite. More diabase solidities. Exaggerated in size in the sketch.

4. The bulk of the diabase forms in the lower half of the chamber, having separated either by settling or some other process from the more acid magma above. Olivine, plagioclase, magnetite, and augite crystallize together, leaving intermediate magma. Further movements facilitate some stoping, by which fragments of the roof, both quartzite and diabase of early solidification, are included in the intermediate magma. (In the sketch these are exaggerated in size, but in the field they are abundantly present as small blocks.)

5. The solidification of the gabbro zone is ended. Above it the intermediate rock solidifies, and the residual granite magma cools to fill the remaining space with red rock. The granite magma just before solidification also intrudes and stopes its roof and assimilates some of the diabase and anorthosite that solidified early, but is still very hot. The final solidification of granite closes the magmatic history. Erosion has exposed some parts of the differentiated series.

formed early and was intruded from below by a later granite magma, residual from the separation of an olivine gabbro near the base. This sequence is shown clearly in Figure 31.

This conclusion gives the sill a broad general interest, for it suggests that the anorthosites may be derived from the same magma that yields the common rock series from granite to gabbro. The petrologic association seen in this sill is that found in nearly all large masses of anorthosite, as contrasted with that in the smaller masses in the small sills in Minnesota.

A question may be raised as to the mechanics of the separation of labradorite rock partly above and partly below the silicic differentiates. If labradorite is light enough to float up from the primary magma into the anorthosite, it cannot at the same time be heavy enough to settle down into the olivine gabbro. The anomaly is perhaps best explained by the early growth of some large labradorite phenocrysts, which would tend to rise much more rapidly than smaller crystals of the same density. The growth of the heavier minerals may be supposed to have begun when the main magma was largely freed of such phenocrysts. Then, although the labradorite was lighter than the magma, a good deal of it might be entangled in a swarm of settling magnetite, augite, and olivine, forming olivine gabbro.

This outline of a possible process, however, is wholly theoretical and is based on the popular notion of crystallization differentiation. It is purely suggestive, but it is in harmony with the field observations, according to which the anorthosite occurred near the top of the sill, apparently having floated up, and the great bulk of underlying magma then evolved into a series of rocks in gravitative arrangement. This evolution, whatever its mechanism, resulted in a series of rocks and an arrangement analogous to those in scores of other well-known igneous masses.

ORIGIN OF THE RED ROCK (GRANITE)

Points of agreement and disagreement.—Bayley,[17] who in 1885 and 1888 made the first careful study of the rocks of Pigeon Point, concluded in conformity with the prevailing hypotheses of that time that some quartzite had been fused to make granite. This conclusion was agreed to by Winchell[18] in the *Final Report of the Minnesota Geological Survey.* In 1917 Daly[19] expressed the belief that the granite was formed by syntexis and that it involved both the assimilation of quartzite and a differentiation that largely masks the earlier assimilation. In contrast to this Daly discussed a third hypothesis, that of "pure differentiation," quite independent of the quartzite.

[17] *Op. cit.* In a later note in the Proceedings of the Twelfth Geologic Congress (page 250) Bayley is inclined to believe in some assimilation rather than fusion of quartzite, but believes that assimilation had no very great effect on the magma.

[18] N. H. Winchell, *Final Report of the Minnesota Geological and Natural History Survey,* Vol. 4.

[19] *Op. cit.,* p. 423, 448.

The information available today would probably enable all petrographers to agree to the following statements:

1. The fact that granite contains about twice as much alkali as either quartzite or gabbro indicates that the granite was formed by differentiation rather than by the fusion of quartzite or by simple solution of quartzite in gabbro.

2. Several facts strongly indicate some assimilation: the occurrence of granite near quartzite; the occurrence in intermediate rock of granite rims around quartzite inclusions, which seem to be corroded; the local occurrence of quartz in gabbro near inclusions of sedimentary rock; and the occurrence of microscopic fragments of quartzite in seemingly clear granite and of some graphite in the igneous rocks near the included sediment.

3. The magma as intruded was probably somewhat hydrous, and juvenile water probably emanated from it.

4. The slate and quartzite of the roof, floor, and especially of the inclusions, contained water, some of which may have been added to the juvenile magmatic water.

5. Whatever may have been the source of the water in the granite magma, the differentiation of that magma toward the top of the chamber accounts for the greater contact effect on the quartzite above the sill than on the sedimentary rock below it.

Daly, favoring syntexis, objects to the "pure differentiation" hypothesis [20] for three main reasons: (1) Many thick sills in both this and other regions consist of gabbro without red rock (granite); (2) water is available in the wall rocks; (3) there are signs of consanguinity of red rock (granite) and quartzite and signs of assimilation of quartzite.

Relation of granite to size of sill.—The work of the Minnesota Geological Survey shows that in this region the development of granite appears to be definitely related to the size of the sills and not to the nature of the rocks in the roof and floor of the sill nor to those in the walls of the conduit. The Pigeon Point sill, which contains a larger proportion of granite than any other sill in the Rove slate area in Minnesota, is considerably thicker than the others.

Granite magma and water.—The fact that the wall rocks contain water cannot justify the assumption that much water passed from them into the magma. [21] The well-known fact that many magmas give off hydrous emanations makes it seem unlikely that a wall rock which receives water from a magma should contribute water to the magma. At Pigeon Point the normal character of the average rock of the whole sill makes it unlikely that the original magma differed essentially from many other magmas that yielded juvenile water. Water was apparently abundant enough in the intrusive magma to pass into the walls, for the granite stringers in the quartzite roof contain numerous miarolitic cavi-

[20] *Op. cit.*, p. 436.
[21] Daly, *op. cit.*, p. 445.

ties, and the quartzite is reddened by red feldspars developed by contact metamorphism. The igneous rock of the sill, as shown by analysis, contains about one per cent of water, and the primary magma probably contained much more. The possible presence of resurgent water in the rock need not be denied, but it seems wholly unnecessary to explain all the facts, and the mechanism of the introduction of water into the magma is very questionable.

The composition of the contact rocks, moreover, does not support the hypothesis that water was driven into the magma from the walls. Much of the sedimentary rock next to the Pigeon Point sill is quartzite, which was certainly not so hydrous as the slates above and below many other sills in the region; but these other sills have no granite phase. Again, at Pigeon Point moderate contact metamorphism seems to have actually increased the quantity of water in the quartzite and to have reduced it very little in the slate,[22] leaving as much water in the invaded sedimentary rock as is found in this region in the average slate and quartzite not affected by contact action. In a few places where the quartzites are reddened and most altered, water seems to have been driven out of the sedimentary rock by heat. It may not have been driven into the still hotter magma, however; most of it probably passed into the sedimentary rock overlying the contact zone.

Although little, if any, water passed into the magma from the contact zone, blocks of the roof were stoped into the magma and did add water to it. The amounts of water added by this and other processes may be estimated. Studies made at Kilauea [23] indicate that the water content of average basaltic magma is about 4 per cent. This percentage is acceptable for the Pigeon Point magma, particularly, because of the following more or less related facts: The water content of the olivine diabase on Pigeon Point is more than 1 per cent after solidification; and although basalt magmas may contain less water than more silicic magmas, the average igneous rock contains about 1.15 per cent water, and the average diabase nearly 2 per cent.[24] Silicic magmas, such as form pitchstone and pegmatitic granite, may contain 10 per cent of water. Many observations show conclusively that magmas contain more water than the igneous rocks formed by their crystallization. The estimate of 4 per cent of water in the primary magma of this sill is therefore not unreasonable.

In contrast to these probable percentages of water in the magmas, the water in the average sedimentary rocks of Pigeon Point is about 2.22 per cent. No doubt some originally contained more than they do now, but no rocks in the district, even if far from the intrusive magmas, have much over 4 per cent of water. It may reasonably be estimated, therefore, that the sedimentary rocks were dehydrated from a content of 4 per cent of water to their present content. Bayley describes three

[22] See analyses reported by Bayley, *op. cit.*
[23] G. W. Tyrrell, *Principles of Petrology* (New York, 1927), p. 47.
[24] R. L. Daly, *Igneous Rocks and Their Origin* (New York, 1914), p. 21.

zones of contact action. The outer zone is not noticeably dehydrated;[25] the central and inner zones are slightly dehydrated; the six analyses available show an average of over 2 per cent of water. As some of the water may escape instead of being forced into the magma, it is fair to estimate that two-thirds of the contact rocks contributed water to the magma to the extent of 2 per cent of their weight. The area of contact rocks mapped by Bayley is about one-sixth as large as the area of the sill. If two-thirds of this area contributed water, the volume of rock contributing is about one-ninth as great as the volume of the magma (two-thirds of one-sixth=one-ninth). That is, one part of quartzite will contribute water to the extent of 2 per cent of its weight to a magma having a volume nine times as great. This contribution would probably increase the water content of the magma about .2 per cent. More accurate calculations, based on specific gravity, are not justified by the rough estimates that were used.

It is more difficult to estimate how much sedimentary rock has been dissolved, but even with regard to this a limit may be set. If we start with the composition of the diabase, the mean composition of the sill on Pigeon Point, or the average diabase of the world, and make successive additions of sedimentary rock that has the mean composition of that on Pigeon Point, we find that the mixture seems normal enough until the additions amount to about 20 per cent of that mixture. With an addition of 20 per cent the mixture becomes a labradorite rock containing considerable quartz, an odd rock that would at once be suspected of contamination. As the mean composition of the sill on the point is not so odd, an estimate of 20 per cent contamination is liberal. If 20 per cent of the present rock is derived from sediments that contained 4 per cent of water, the magma resulting from this mixture would contain about 20 per cent of 4 per cent, or .8 per cent, of resurgent water. This calculation applies to all assimilated material, including that from conduits as well as that from the roof of the sill chamber.[26]

Thus, even if the most liberal allowance is made for assimilation and for connate water driven into the magma from the walls by gas pressure, the total water added to the magma will be scarcely 1 per cent of the magma and probably much less. In comparison with the 4 per cent of water that was probably in the primary magma (of which over 1 per cent remains in the rock), the additions of connate water from the sedimentary rock must be of little significance. Additions of water from the sedimentary rock would probably not have induced much more rapid or more thorough differentiation than would have occurred in the hydrous magma without additions.

Evidence of assimilation of quartzite and of its consanguinity with

[25] Bayley, *op. cit.*, p. 84, 88, 97, 98.

[26] Those who argue most strongly for the effects of connate waters are forced to shift their ground continually. If it is shown that the walls of the chamber do not contribute enough, they appeal to a conduit. If that does not contribute enough, they appeal to a deeper reservoir that fed the conduit; but in such deeper chambers the terms assimilation and addition are misleading; the action in the deeper chambers is magma generation.

granite.—It has been shown that the granite phase of the Pigeon Point sill may have been derived from the original injection by magmatic differentiation, a process favored by the great thickness of the sill. This possibility, however, is not sufficient to remove from all consideration the other processes by which granite magma may be formed. Daly[27] notes a consanguinity of the granite and the sedimentary rock and believes the sediments had a good deal to do with the formation of the granite. The work of the Minnesota Geological Survey has not tended to support this view.

In the first place, the supposed consanguinity would relate the granite to a contact-altered quartzite rather than to unaltered sedimentary rock. If such a metamorphosed quartzite shows a relationship to a granite near by, the relationship probably results from the thorough permeation of quartzite by magmatic emanations, and, as shown above, it is not probable that the sedimentary rock assimilated by the magma furnished any considerable amount of these emanations.

In the second place, graphic intergrowths, which occur not only in granite but abundantly in the contact rock, are the most important signs of consanguinity. Space does not permit a thorough discussion here of the origin of such intergrowths. Fenner[28] has recently shown that some micrographic intergrowths are to be attributed to recrystallization, some to introduction and replacement, others to deuteric action (late magmatic reactions), and still others possibly to primary crystallization. In a study of the rocks at Pigeon Point in an attempt to ascertain their mode of origin it was found that some micrographic structures in the quartzite seem clearly due to rearrangement of its original material and others to emanations from the magma. Such emanations, however, seem not to have been abundant enough to make any marked change in the composition of the quartzite.

Indigenous graphic intergrowths in the quartzite that resemble those in the red rock can hardly be considered proof of the consanguinity of the two rocks, however, for such intergrowths may originate in various ways. As Daly asserts, the real evidence of consanguinity in such a case, and in this particular case, is the association of the two rocks. He says:[29] "Nor is it likely that the close field association of the micropegmatite in the red rock with the micropegmatite in the metamorphosed sediments is a pure accident. The material is of a nature too specialized for that. The explanation is probably to be found in the red rock material having been chiefly derived from dissolved quartzite and metargillite." Further work of a very detailed character has shown that the field association of quartzite and red rock (granite) is not so close as was supposed.

[27] *Op. cit.*

[28] C. N. Fenner, "The Katmai Magmatic Province," *Journal of Geology,* Vol. 34, No. 7, Part 2, p. 750 (1926).

[29] Daly, *op. cit.,* p. 439–440.

Though some granite may form by assimilation of quartzite, the present authors maintain, for the following reasons, that most of the granite on Pigeon Point did not have such an origin:

1. The map here presented (see Figure 29) shows that the field association of the granite and the quartzite is less uniform than earlier maps indicated. Nearly everywhere diabase or porphyry or anorthosite intervenes between the granite and the sedimentary roof.

2. In a few places the exposures indicate some solution of quartzite in gabbro, but the resulting contaminated rock is a quartz gabbro.[30] The quartz in this rock occurs in irregular and club-shaped masses. If the main granite phase of the sill originated from this contaminated quartzose magma, the graphic structure of the granite was a distinctly later development, caused by differentiation and in no possible way related to the graphic structure in the quartzite inclusions that were dissolved. In other words, the graphic quartz of the quartzite inclusions would have had to pass through the phase of non-graphic quartz gabbro before it became graphic granite.

3. The assimilation was probably much less than Daly believed, not even approaching the limit of 20 per cent as calculated above; more assimilation than that would make this or any other probable primary magma evidently hybrid.

If red rock (granite) was formed from quartzite, the granite, being rich in alkalies, would have to use up the alkalies of about three parts of quartzite to make one part granite. The two parts of "residue" from this extraction would be a peculiar mixture of silica, alumina, and ferric oxide, without much alkali. No such rock is known, and if the granite was formed by magmatic heat this residue also was probably incorporated into some magma. The intermediate rock already mentioned comes to mind at once as the probable destination of the residue. It should be noted, however, that there was twice as much quartzite "residue" as there was granite, and if its volume was further increased by mixing with gabbro to make intermediate rock, there would be four times as much intermediate rock as granite. In actual exposures there is less intermediate rock than granite. This shortage of the "by-products" of the supposed formation of granite from quartzite and gabbro makes it appear unlikely that much assimilation occurred.

Furthermore, the dissolving capacity of the magma may not have been so great as Daly believed. He suggested that the granite magma, even at a late stage, was capable of assimilating considerable amounts of an earlier plagioclase rock.[31] This plagioclase rock, however, was an early differentiate of the same magma that formed the granite, and the fact that the granite magma attacked it while still hot does not indicate that the magma vigorously attacked the cooler quartzite in the roof.

Finally, the average basaltic magma contains all the elements needed

[30] Bayley, *op. cit.*, p. 101.

[31] *Op. cit.*, p. 442–443.

to produce such a granite as the red rock in considerable quantity,[32] perhaps 10 per cent of the whole mass. Any excess of granite may possibly be attributed to syntexis. If the granite forms about 13 per cent of the sill (a fair estimate), probably not more than 3 per cent is a product of syntexis; and it is almost certain that the other 10 per cent would have differentiated if there had been no solution of wall rocks.

The facts thus presented have great cumulative weight in indicating that the granite was formed almost entirely by magmatic differentiation. There was some assimilation, but it seems to have been of slight consequence.

Shells of red rock around inclusions.—Bayley describes especially significant shells of red rock (granite) around inclusions of quartzite that are found in intermediate rocks.[33] If the granite had been formed by fusion or by assimilation without differentiation, such a granite should have the composition of a rock that could have been derived from the adjacent rocks. It has not such a composition, for it contains more alkali than either of the adjacent rocks. (Tables 9 and 10.) Daly considers these shells at length:[34] (1) The shell may be fused quartzite from which excess material rapidly diffused away; (2) the shell may have been "sweated out" of the inclusion; (3) some of the quartzite may have been assimilated and some of the alkali added by concentration from the magma. The third suggestion is more in harmony with the field facts than the others.

How such a concentration of alkali occurred is an unanswered question. It has been suggested that inoculation by some mineral from the inclusion, or by water, might start a differentiation that would otherwise have been inconspicuous. How an inclusion might cause or modify a differentiation in a magma without making any notable contribution to the magma is obviously a puzzling question. Nevertheless, there are evidences of such action in several places.[35]

Summary of Processes in Logan Sills and Intrusions

After the intrusion of diabase magma, small to medium-sized bodies of magma were rapidly cooled to rather uniform rock with normal gradations from fine-grained or glassy borders to average diabase centers. In certain large and medium masses an early stage of crystallization produced labradorite phenocrysts. Some of these became aggregated into masses of gabbro and anorthosite, not only in sills but in some dikes. In the larger sills the labradorite showed an evident tendency to rise.

The main magma then differentiated, yielding a large body of olivine gabbro with a little granite above it. At the time of intrusion and probably thereafter until most of the magma had crystallized, there was

[32] F. F. Grout, "Calculations in Petrology," *Journal of Geology*, 34:548 (1926).
[33] *Op. cit.*, p. 110.
[34] *Op. cit.*, p. 440–443.
[35] F. F. Grout, "Anorthosite and Granite as Differentiates of a Diabase Sill on Pigeon Point, Minnesota," *Bulletin of the Geological Society of America*, 39:555–578 (1928).

some assimilation of the wall rocks and especially of their fragments. There is no evidence that as much as 20 per cent of the magma was of this origin, but the occurrence of some siliceous phases near siliceous wall rocks and fragments is strong indication of some solution. The effects of the intrusives on the wall rocks that remain unassimilated have been noted in the description of those sediments. Naturally the red rock (granite) had a somewhat different effect from that of the diabase.

Alteration and Age of Logan Sills

The Logan sills and intrusives at the eastern end of the area here mapped seem to be the latest igneous rocks formed; but from Gunflint Lake east to Stump Lake or a little beyond, those sills and dikes that outcrop near the Duluth gabbro are somewhat modified. Very close to the gabbro the small diabase bodies are recrystallized to a hornfels that is hardly distinguishable from the slate hornfels. In certain places a porphyritic diabase has been recognized in the hornfels by its phenocrysts, which are not wholly lost in the contact metamorphism. The groundmass, however, has entirely lost its diabasic texture. It has been possible to follow the stages of recrystallization very clearly, and some traces of diabase texture may persist among the rounded grains of augite and plagioclase up to within a few feet of the gabbro.

No red rock (granite) phase of the sills and dikes has been traced into the contact zone of the gabbro, but if they occur there, they also would no doubt be somewhat recrystallized.

The age of the Logan sills and the dikes evidently related to them is fairly well determined by the facts already noted. They intrude rocks from the basement complex up, including the sediments and flows of the middle Keweenawan, and at least part of them are metamorphosed by the gabbro, which is believed to be late-middle Keweenawan. Probably, therefore, the Logan intrusives are middle Keweenawan.[36] This argument is weak in one respect, however; it assumes that all the Logan intrusives are of one period. It is not impossible that such diabase was intruded partly in Animikie time and from then on at intervals to the end of the Keweenawan. Careful search was made for diabase pebbles in the basal conglomerate of the Keweenawan, and for unconformable relations of the conglomerate toward the diabase, but they were not found. Probably the best evidence of age is the occurrence of two dikes that can be traced through from the Rove area into the Keweenawan flows to the south. These dikes are in Sec. 3, T. 63 N., R. 5 E., and Sec. 7, T. 63 N., R. 6 E. (See Plates 12 and 13.)

[36] Clements in United States Geological Survey Monograph 45, pages 408–419, discusses critically the views of Lawson and of Grant as to the age and relation of the sills and gabbro. His conclusion that the two kinds of intrusive are equivalent would now be changed by the new finding of sills clearly metamorphosed by gabbro action.

ECONOMIC GEOLOGY

General Relations

The Rove slate area in Canada contains mineral deposits that are estimated[1] to have produced slightly over $5,000,000 in silver. Of this amount the Silver Islet mine is credited with $3,250,000. Other important mines are the Silver Mountain, with a production of $500,000, the Beaver, which produced $550,000, and the Badger and Porcupine, which are credited with $300,000 each. Descriptions of most of the mines and prospects have been given by Ingall[2] and more recently by Tanton.[3]

The veins contain as gangue minerals calcite, quartz, barite, and fluorite, and all these except fluorite have been found in the veins of the Rove area in Minnesota. The metallic minerals are native silver, argentite, sphalerite, galena, pyrite, chalcopyrite, and chalcocite. Sphalerite is the most abundant mineral, followed by galena and pyrite in the Canadian deposits.

The deposits lie in two east-west belts, the northerly one extending along the head of Thunder Bay and the southerly one along the islands at the entrance to the bay. It is at the western end of the latter belt that the Minnesota deposits are found. It is evident that the Minnesota deposits are part of the group, but thus far no deposits of commercial importance have been discovered on this side of the international boundary, though deposits of copper, nickel, graphite, and barite have been prospected in places. In Canada, veins of the silver-bearing type are known to occur as far west as the region of North Lake on the international boundary.[4]

Types of Veins

The following types of veins and mineralization were observed during the present investigation:

1. Calcite veins
2. Calcite-barite veins
3. Calcite-sulphide veins
4. Calcite-barite-sulphide veins
5. Quartz veins
6. Xonotlite-prehnite-sulphide veins
7. Sulphide diabase
8. Graphite disseminations

The first four are closely related, and better exposures of some of the veins of types 1 and 2 would doubtless cause them to be classified as either 3 or 4.

[1] Eighteenth Annual Report of the Ontario Bureau of Mines, 1909, Part 1, p. 12.

[2] E. D. Ingall, Annual Report of the Geological and Natural History of Canada, Vol. 3 (1888).

[3] Tanton, *Fort William and Port Arthur, and Thunder Cape Map Areas, Thunder Bay District, Ontario* (Memoir 167, Geological Survey of Canada, 1931).

[4] J. E. Gill, "Gunflint Iron-bearing Formation, Ontario," Summary Report of the Geological Survey of Canada, 1924, Part C, p. 44.

The tabulation below classifies and gives the location of the veins concerning which data are available. Descriptions of each of these will be found in the township reports.

1. Calcite Veins
   SW¼ SW¼ Sec. 33, T. 65 N., R. 1 W. Pit.
   NE¼ NW¼ Sec. 3, T. 64 N., R. 3 E. Outcrop.
   SE¼ Sec. 12, T. 64 N., R. 3 E. Outcrop.
   NE¼ SW¼ Sec. 35, T. 64 N., R. 5 E. Pit.
   NW¼ SE¼ Sec. 21, T. 64 N., R. 5 E. Outcrop.
   NE¼ NE¼ Sec. 28, T. 64 N., R. 5 E. Outcrop.
   SE¼ SE¼ Sec. 35, T. 64 N., R. 5 E. Outcrop.
   NE¼ SW¼ Sec. 35, T. 64 N., R. 5 E. Pit.
   SE¼ NE¼ Sec. 19, T. 64 N., R. 6 E. Outcrop.
   SE¼ NW¼ Sec. 31, T. 64 N., R. 6 E. Outcrop.
   NE¼ NE¼ Sec. 31, T. 64 N., R. 6 E. Outcrop.
   Shore of Lake Superior, Sec. 31, T. 64 N., R. 7 E. Outcrop.
   Shore of Lake Superior, Sec. 32, T. 64 N., R. 7 E. Outcrop.
2. Calcite-Barite Veins
   Shore of Pigeon Bay, Sec. 28, T. 64 N., R. 7 E. Outcrop.
   Shore of Lake Superior, Sec. 27, T. 64 N., R. 7 E. Pit.
   SE¼ Sec. 32, T. 64 N., R. 7 E. Pit.
   Small island west of Lucille Island.
   Southern end of Susie Island and small island off point.
3. Calcite-Sulphide Veins
   E½ Sec. 24, T. 64 N., R. 6 E. Outcrop.
   SE¼ SE¼ Sec. 31, T. 65 N., R. 2 E. Pits.
   SW¼ SW¼ Sec. 32, T. 65 N., R. 2 E. Pits.
4. Calcite-Barite-Sulphide Veins
   Susie Island, Lake Superior. Shafts.
   Near shore on Pigeon Point, Sec. 28 (from Winchell). Shaft.
5. Quartz Veins
   SE¼ Sec. 5, T. 64 N., R. 2 E. Pits.
   NW¼ NW¼ Sec. 5, T. 64 N., R. 3 E. Shaft.
   Secs. 9 and 10, T. 64 N., R. 3 E. (from Winchell). Outcrops.
6. Xonotlite-Prehnite-Sulphide Vein
   SW¼ SE¼ Sec. 35, T. 64 N., R. 5 E. Pit.
7. Sulphide Diabase
   NE¼ SE¼ Sec. 36, T. 64 N., R. 5 E. Outcrop.
   NE¼ SW¼ Sec. 35, T. 64 N., R. 5 E. Pits.
   NE¼ NE¼ Sec. 31, T. 64 N., R. 6 E. Outcrop.
   SW¼ SW¼ Sec. 29, T. 64 N., R. 6 E. Outcrop.
   SW¼ SE¼ Sec. 35, T. 64 N., R. 5 E. Pits.
   SW¼ NE¼ Sec. 6, T. 63 N., R. 6 E. Outcrop.
   SE¼ SE¼ Sec. 29, T. 64 N., R. 6 E. Pit.
   SE¼ NE¼ Sec. 28, T. 64 N., R. 6 E. Outcrop.
8. Graphite
   SE¼ Sec. 32, T. 64 N., R. 7 E. Pits.
   NW¼ NE¼ Sec. 36, T. 64 N., R. 5 E. Outcrop.

Description of Particular Deposits

The several types of calcite veins are without doubt variations of a single genetic series of veins. They are usually fissure fillings, and they range from an inch or two to several feet in width. Fragments of the country rock are commonly cemented by calcite and other vein minerals to form a vein breccia. The possibility thus exists that some of the veins occupy fault fissures. There is little evidence of replacement of the wall rock. Quartz is found in some of the calcite veins on Pigeon

FIGURE 32. — Microphotograph of a thin section of a sulphide diabase. Note fresh olivine (O) and plagioclase (P). Black area is sulphide. Pit SW¼ SE¼ Sec. 35, T. 64 N., R. 5 E. Mag. x 34.

FIGURE 33. — Pyrite remnants in bornite. Susie Island. Mag. x 75.

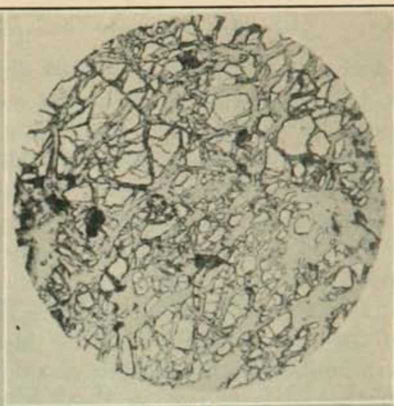
FIGURE 34. — Bornite (B) with bornite-chalcopyrite (white) fringe. Probably a replacement of chalcopyrite by bornite. The black is calcite. Susie Island. Mag. x 38.

FIGURE 35. — A mass of chalcocite (C) surrounded by bornite (B) and the latter by chalcocite (dark). The zone of bornite between chalcocite and calcite is characteristic of these ores. Susie Island. Mag. x 34.

FIGURE 36. — A ring of chalcopyrite in bornite. Susie Island. Mag. x 75.

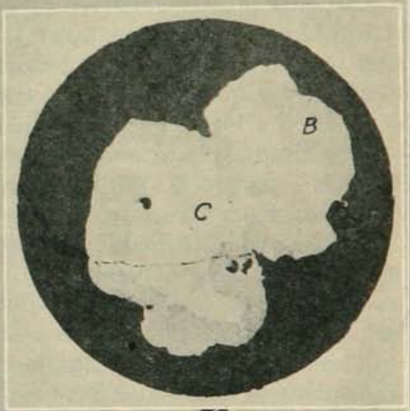
FIGURE 37. — Lattice intergrowth of bornite (dark) in chalcopyrite (light). Probably a result of replacement. Susie Island. Mag. x 75.

32

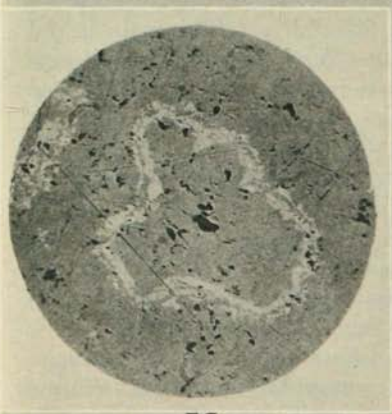


33

34



35



36

37

Point and Susie Island and is abundant in the veins across the border in Canada; so the few quartz veins noted may result from the same processes that formed the calcite series.

The xonotlite-prehnite-sulphide vein is exceptional and is described in detail below. The sulphide diabase was apparently formed by crystallization as a part of the igneous rock. Small amounts of vein sulphide probably occur with the sulphide diabases, but most occurrences seem to be relatively unaltered igneous rock.

The Susie Island deposits.—These veins are the most striking found in the area described in this report.[5] They cross both the dikes and sediments in approximately vertical fractures. The detailed geology of the island is shown in Plate 15 and is discussed in the township description. The veins weather out as grooves between the walls, but as they are largely calcite they are conspicuously white where exposed. A few exposures of veins over 12 inches thick are found on the island, but they pinch and swell locally, so larger masses may be expected. Some wider veins have been reported in the drift east of the incline shaft of the Susie Island mine.

The older exploration on the south side of the east point of the island is a shaft said to be 150 feet deep on a vein 12 inches wide. A drift to the south from the bottom of the shaft is reported to have followed a vein 7 feet wide. A drift to the north followed a narrower vein. Ore was piled on the dock for shipment, but a heavy storm wrecked the dock and hoist and scattered the ore along the beach, where it is now found as peculiar white bowlders containing fairly fresh copper sulphides.

The inclined shaft of the more recent exploration was sunk from the high point of the island, on the breccia zone between two dikes. From a depth of 210 feet a drift ran 60 feet, N. 70° E., to a vein that runs about N. 20° W. A few tons of ore were sacked for shipment, but operations ceased because of the death of the principal owner. The ore sacked contained 6.22 per cent of copper and a little silver. This vein is not conspicuous but can be found at the surface. A much more conspicuous vein lies 120 feet east of the incline, but it is said that the drift from the incline did not reach it.

Traces of other mineral veins can be found at other points on the island and on the mainland. Calcite-barite veins, some of them several feet wide, are found in several places on Pigeon Point.

The gangue minerals are not numerous. The veins are largely calcite and sulphides, but barite is locally abundant and was found in thin section intergrown with coarse calcite. The calcite shows a conspicuous dark zoning parallel to the rhombic cleavage. Polished surfaces show this to be due to numerous minute inclusions of chalcocite arranged parallel to the cleavage. Quartz and chalcedony are abundant in some thin sections, and quartz crystals line some small vugs. There was evi-

[5] G. M. Schwartz, "Copper Veins on Susie Island, Lake Superior," *Economic Geology*, 23:762–768 (1928).

dently more silica in the vein material than might be expected from the hand specimens. No other gangue minerals of importance were found.

The thin sections as well as the polished surfaces indicate that much of the sulphide ore is later than the calcite, but the occurrence of inclusions of chalcocite in the zoned calcite indicates the presence of copper sulphides during the deposition of the calcite. No doubt the periods of their deposition overlapped.

The ore minerals in order of abundance are bornite, chalcocite, chalcopyrite, pyrite, covellite, and malachite.

Bornite is found in most of the 50 polished specimens available, and in 7 it was the only abundant sulphide. The most striking occurrence of bornite is in the more or less zoned structures with chalcopyrite. (See Figures 34–36.) The relations shown by these two minerals are complex and difficult to explain. Similar structures for these minerals have not been described, so far as is known. The lattice-like intergrowth (see Figure 37) present in many specimens resembles the structures attributed by some investigators [6] to the breaking down of a solid solution; but other relationships show that these particular structures are due to replacement of chalcopyrite by bornite. This lattice type of structure is common in the bornite-chalcopyrite specimens and assumes a variety of forms. In some specimens the sulphides form a series of scallops along the gangue, and there is more or less of an alternation of the two sulphides. (See Figure 34.) In some specimens bornite occurs in the spherical area of chalcopyrite as a network of minute veins; in others the entire center of the concentric mass of sulphide is bornite, and around the outside chalcopyrite is replaced by a network of bornite that assumes a lattice structure.

Bornite occurs also in chalcocite related to cracks and gangue boundaries, indicating a late development of bornite. In nearly all specimens where bornite occurs with chalcocite it shows a preference for the calcite boundaries, as shown in Figure 35.

Chalcocite occurs in a variety of relations in the ores. It occurs in greatest abundance as a replacement of pyrite. Pyrite was evidently abundant as an early sulphide, and it has been brecciated and replaced by all the later sulphides. Chalcocite, which appears in hand specimen to be nearly pure, is found on polishing to be filled with innumerable minute remnants of pyrite. The writer estimated that there were 1,200 or more fragments of pyrite in a single field of a microscope with an 8 millimeter lens. This is equivalent to 85,000 fragments per square centimeter of surface.

In some specimens, pyrite-chalcocite areas are almost enclosed in bornite. The development of these areas seems to be somewhat as follows: Pyrite, the earliest sulphide, was brecciated and replaced by

[6] See, for example, R. W. Van der Veen, *Mineralography and Ore Deposition* (The Hague, 1925), Figures 45, 46, and 50, and page 47.

copper solutions. The pyrite was directly replaced by chalcocite but surrounding areas were filled by bornite, which may have replaced calcite. In any event, the pyrite seems to have favored in some way the development of chalcocite. Chalcocite also occurs intimately associated with bornite that is disseminated in calcite. Some specimens of chalcocite contain remnants of calcite. Much of the chalcocite shows a complete independence of visible channels, cleavage, or mineral boundaries, so its hypogene origin seems obvious. A small amount occurs along minute cracks associated with covellite and is evidently supergene.

One specimen of ore from the old shaft shows with moderate magnifications an apparent gradation from chacocite to bornite. Bornite and chalcocite are disseminated in calcite, and in areas containing both the bornite shows the usual preference for the gangue boundaries. Examination of the gradational zone at high magnifications shows a series of blades of bornite in the crystallographic directions of the chalcocite. This type of structure has been artificially produced by the slow cooling of a solid solution of bornite and chalcocite.[7] There is such a marked similarity between the natural and artificial intergrowths that a similar origin seems likely.

Chalcopyrite is found in a majority of specimens and is apparently the earliest copper mineral, since in most specimens it does not replace earlier sulphides. A small amount of late chalcopyrite replaces bornite along cracks and cleavages. This is so different from the main mass of the mineral that it is undoubtedly a distinct generation, possibly supergene. Chalcopyrite is usually associated with bornite, which occurs with it as a lattice intergrowth, as a network of veins, and in the scalloped and concentric structures noted under bornite.

Two types of specimens contain abundant pyrite. Some specimens of chalcocite ore that seem pure are in many cases filled with minute pyrite remnants, which may make up nearly 50 per cent of the specimens. Other specimens show a similar replacement of pyrite by bornite. In a rare type, chalcopyrite appears to replace pyrite. The normal course seems to be a direct replacement of pyrite by chalcocite.

Covellite is not an abundant mineral, but it is rather widespread. A small amount is found as large grains associated with chalcocite in a way that indicates a primary origin, but most of the mineral occurs as veinlets and tufts, replacing other sulphides in a manner characteristic of supergene replacement. Bornite seems to yield covellite more easily than does either chalcocite or chalcopyrite.

Even a casual examination of the Susie Island ores brings out the peculiar concentric structure, rosette shaped and scallop-like, of the sulphides in the calcite. A few of these are illustrated in the accompanying figures, but additional photographs would be necessary to convey an adequate idea of these unusual structures, which have not been

[7] G. M. Schwartz, "Experiments Bearing on Intergrowths of Bornite and Chalcocite," *Economic Geology*, 23:381–397 (1928).

noted in other copper deposits. They recall at once the ore of Cobalt and of Silver Islet, and it seems that the calcite gangue of all these deposits is in some way responsible for the concentric structures. This has been suggested by Guild. Perhaps his ideas may be applied also to the Susie Island ores. Guild's conclusion is as follows.[8]

> The peculiar concentric structure seen in the cobalt nickel minerals is believed to be due to the habit of the early mineral, smaltite, to replace calcite in the form of concentric shells. The later minerals replacing the remainder of the calcite inside the shells completes the structure. The spaces between the shells are sometimes filled (by replacement of calcite) with the earlier mineral smaltite, less often by the later mineral niccolite.

Lindgren[9] has attributed the colloform structure to gel replacement of a crytalline carbonate filling. He believes that the metals at Cobalt were introduced as chlorides mixed with arsenic sulphide and hydrogen sulphides or alkaline sulphides. The solutions were neutralized, and sulphides together with sulphur and arsenic were precipitated as a complex gel. The complex gel was almost immediately transformed into crystalloids, and this resulted in the mixture of minerals now found in these deposits.

It is not uncommon to find that a given deposit shows a more or less uniform sequence of minerals. This condition might be expected in the series of small veins on Susie Island, but the paragenesis is neither uniform nor simple.

Of the sulphides, pyrite was invariably the earliest. In many specimens it was directly replaced by chalcocite, and in these no further change took place. More rarely, pyrite was replaced by bornite or by chalcopyrite, but no successive replacement of pyrite by chalcopyrite, bornite, and chalcocite was observed.

Chalcopyrite, bornite, and chalcocite were in part deposited without obvious replacement of earlier sulphides. They seem to be true primary minerals. Much of the chalcopyrite was replaced by bornite and bornite by chalcopyrite, presumably supergene. Chalcocite was replaced by bornite, but, strangely enough, there is no clear evidence that bornite is replaced by hypogene chalcocite. They seem to be contemporaneous in several specimens. Rarely a little supergene chalcocite was developed in bornite, but covellite was much more common as a supergene sulphide.

According to Lindgren, the lack of a definite order of crystallization of the minerals is characteristic of minerals formed by gel replacement.

In addition to the copper veins on Susie Island described above, small calcite-barite veins are found near the southern tip of the island. Similar veins occur on the small island just west of this point, as well as on the small island northwest of Lucille Island. The principal minerals of these veins are the same as the gangue minerals of the copper veins.

The Green prospect.—Very different is the xonotlite-chalcopyrite deposit in diabase in a shallow pit in SW¼ SE¼ Sec. 35, T. 64 N.,

[8] F. N. Guild, "A Microscopic Study of the Silver Ores and Their Associated Minerals," *Economic Geology,* 12:293–353 (1917).

[9] W. Lindgren, "Metasomatism." *Bulletin of the Geological Society of America,* 36: 247–262 (1925).

R. 5 E.[10] It is but a short distance from State Highway No. 1 and was discovered by the owner, Mr. Melvin Green. Other occurrences of sulphides in diabase resembling the deposit on the Green homestead were observed in several places, as shown on page 61.

The test pit followed vertical fractures and replacement veins in a diabase dike near the contact with slate. Specks of sulphides may be seen disseminated through the diabase, but along the fractures are masses consisting principally of sulphides with residual fragments of diabase, much of the original rock having been replaced by sulphides. The sulphides are most extensive where fractures intersect and include in places masses of xonotlite ($5CaO \cdot 5SiO_2 \cdot H_2O$) and prehnite.[11] The manner in which the silicates are embedded in the sulphides indicates that they were deposited at the time the vein was formed. The sulphides in the diabase are not confined to the deposit at this particular pit but are found in places over an area of several square miles. They are apparently near the contact of diabase and slate but have not been found directly at the contact or in the slate.

A study of thin sections and polished surfaces of the wall rock outside the fractured zone and of sulphides and fragments of diabase found in the fractured zone reveals a remarkable contrast.

Thin sections of the rock a foot and more from the vein show a well-developed diabasic texture. (See Figure 32.) The essential minerals are plagioclase (labradorite), olivine, and augite, with accessory pyrrhotite, chalcopyrite, magnetite, and biotite. The only alteration products are small amounts of serpentine in cracks in olivine and an occasional grain of chlorite. Plagioclase makes up from 50 to 60 per cent of the diabase and occurs as euhedral crystals apparently free from alteration products of any kind. Olivine, augite, magnetite, and the sulphides fill in around the lath-shaped feldspars. Magnetite is small in amount and in some cases is intergrown with the sulphides, which are somewhat more abundant than magnetite.

An examination of polished surfaces of the diabase shows that the sulphides in the diabase consist of pyrrhotite and chalcopyrite, the former predominating. The sulphides obviously crystallized later than the feldspar, as is shown by their matrical position and by occasional stringers cutting feldspar crystals.

The residual fragments of diabase found with the massive sulphides in the vein are in marked contrast to that described above. Olivine and augite have largely disappeared but remain in some rocks, showing the original texture. In the majority of cases the rock is intensely altered, and though plagioclase remains as an abundant constituent, it has lost its euhedral form and is filled with alteration products. Chlorite,

[10] G. M. Schwartz, "An Occurrence of Xonotlite in Minnesota," *American Mineralogist*, 9:32–33 (1924), and "A Sulphide Diabase from Cook County, Minnesota," *Economic Geology*, 20:261–265 (1925).

[11] This was erroneously identified as diopside in the article from which this section is taken. See *American Mineralogist*, 10:83–87 (1925).

serpentine, secondary biotite, quartz, sericite, magnetite, and sulphides are more or less abundant, especially serpentine. In places a large grain of augite may be seen partly altered to a mixture of biotite, magnetite, and quartz. Many veinlets contain cross-fibers of serpentine, indicating the incipient development of chrysotile asbestos. In the available thin sections of the altered rock the sulphides vary from small amounts to 50 per cent or more. It is obvious that the sulphides in the veins were, for the most part, introduced during a period of hydrothermal alteration and that they replaced the minerals of the diabase. Rarely, areas of sulphides are found that have the sharp straight boundaries of the original diabase, as in the rock far from fractures. These indicate two generations of sulphides. It is believed that the first generation was of true magmatic origin and that the second was introduced by the hydrothermal solutions connected with the intrusive, and that this probably took place soon after the solidification of the diabase.

A study of polished surfaces shows that the sulphides consist of pyrrhotite and chalcopyrite, with subordinate amounts of pentlandite and violarite.

Magnetite was seen but rarely in the polished ore except in the diabase fragments, where it is a normal constituent. The following partial analysis shows the amount of several elements in selected material: Fe, 32.63 per cent; Cu 18.26 per cent; Ni, 0.52 per cent; S, 26.21 per cent.

Graphite prospects.—Small outcrops in NW¼ NE¼ Sec. 36, T. 64 N., R. 5 E., show graphite nodules in a red rock. These are somewhat unusual in having the graphite in igneous rocks but seem to be in too small amounts to be commercially valuable.

Several pits in SE¼ Sec. 32, T. 64 N., R. 7 E. on Pigeon Point have followed graphitic disseminations in graywacke quartzite. Examination by the United States Bureau of Mines shows this to be of the amorphous type and to be present in such small amounts with siliceous material that it seems doubtful if this material could be utilized commercially even under the most favorable conditions.

Conclusions on Economic Possibilities

The geological conditions in the area of the Rove formation in Minnesota are nearly the same as in the neighboring part of the Thunder Bay region of Canada, where silver mines have been successfully operated. There are, moreover, several veins in Minnesota that carry metals, and it was thought probable that detailed work might lead to results that would aid in prospecting in Minnesota. The veins discovered thus far are small and not persistent. Prospecting is difficult because of the heavy underbrush and also because glacial drift so often covers the contacts of intrusives and slates, where the most favorable conditions should exist for mineral deposition.

A general statement on the prospects found in each township is given at the end of each township description.

TOWNSHIP DESCRIPTIONS

Detailed maps of each township are shown in Plates 1 to 15 and should be referred to in reading the description of each township.

Township 65 North, Range 4 West

Locations.—This township contains the extreme western tongue of the Rove slate as it outcrops at present. Inclusions in the gabbro farther west indicate that it once extended many miles in that direction and probably was continuous with the Virginia slate. The locations in the two sections mapped were determined by reference to the northwest corner of Section 25, where the original corner is marked. No other section corners were found.

Surface features.—Two prominent features determine the topography of this small area. A high northward-facing bluff, or escarpment, marks the approximate contact of the Duluth gabbro with the Rove slate. The slate area is occupied by the broad valley or sand flat of the Cross River. This is comparatively level except for the glacial ridges shown on the map. Glacial drift and alluvial sand cover the slate area so thoroughly that only two slate outcrops were discovered in the township.

Geology.—Little need be said regarding the geology in this small area. The Rove formation which outcrops near the mouth of Cross River is a black carbonaceous slate such as is common in the lower or "black slate" portion of the formation. An analysis of slate from this outcrop is given on page 21.

The only other outcrops of slate are close to the contact with the Duluth gabbro and are very small. The exact place to the west where the slate is finally eliminated and the gabbro comes in contact with the Gunflint iron formation cannot be determined because of the cover of glacial drift, but it is probably in Section 26.[1]

Township 65 North, Range 3 West

Locations.—The locations in this township are fairly accurate, and no serious discrepancies were found in the land survey, as they were in several townships to the east. The section and meander corners that were found to be marked in a dependable manner are shown on the map by small circles; some may have been re-established since the field work was done.

The International Boundary Survey on Gunflint Lake served to check the locations and to tie in the accurate topographic map along the

[1] As shown by Clements in the atlas in United States Geological Survey Monograph 43.

boundary with that of the remainder of the township as mapped by use of barometers.

Surface features.—The topography of this township is rather rough. Elevations range from 1,547 on Gunflint Lake to 2,000 south of Loon Lake. The most prominent topographic feature is the long ridge between Gunflint and Loon lakes. This is characterized by a steep slope to the north and a gentle slope to the south passing beneath Loon Lake, which lies at an elevation of approximately 1,745, 200 feet above Gunflint Lake. The high land south of Loon Lake marks the contact of the Duluth gabbro with the Rove formation and its intrusive diabase sills.

Glacial drift is relatively thin over most of the area, as is shown by the abundant outcrops of diabase and slate. The Gunflint trail extends across the township, following the contact of the gabbro and slate in a rough way.

Geology.—As in most of the western part of the Rove slate area, only three formations of importance are involved. These are the Rove formation, the diabase intrusives, and the Duluth gabbro; the last forms the present southern limit of exposures of the Rove formation for more than 35 miles.

The Rove formation is an alternation of slate and graywacke phases. We have been unable after detailed work to distinguish a separate black slate member, such as was shown on the reconnaissance map.[2] The slate at the mouth of Cross River is a distinct black slate; this does not seem to extend along the south side of Gunflint Lake as a unit but rather as thin beds alternating with coarser beds.

The prominent ridge between Gunflint and Loon lakes is formed by a series of diabase sills in the slate. The cross section at the middle of the township shows three long sills, and smaller ones may be covered. The upper sill, which has been called the Loon Lake sill, is probably somewhat thicker than the average, and it has a decidedly porphyritic top. This makes it possible to trace the sill to the east as far as Lake Louise in Sec. 27, T. 65 N., R. 2 W.

One of the best examples of contact metamorphism of the slate by the sills was noted along a bluff in SW¼ Sec. 29, where the slate from 2 to 10 feet below the sill showed metacrysts of cordierite. (See Figure 16.) There is comparatively little metamorphism above the sill.

The contact of the Duluth gabbro and the slate is a zone showing many excellent exposures, some of them on the road. The slate near the contact is much contorted and has been converted to hornfels. Inclusions of hornfels in the gabbro are common, and often it is difficult to locate the exact contact on account of the mixture of gabbro and metamorphosed slate.

No veins or prospects were found in this township that would indicate

[2] U. S. Grant, *Final Report of the Minnesota Geological and Natural History Survey*, Vol. 4, Plate 69.

the presence of minerals of economic value. The north shore of Gunflint Lake is the type locality for the Gunflint iron formation.

Township 65 North, Range 2 West

Locations.—The locations for this township are fairly accurate except at the east end, where the original land survey corners, although well marked in several places, are obviously not in the positions indicated in the original plat. Where the original section or meander corners could not be found, it was usually possible to check locations closely by the outlines of the lakes, streams, or other features. The International Boundary Survey monuments were valuable checks for the work near the boundary.

The mapping at the east range line, which also involves T. 65 N., R. 1 W., requires some explanation. A meander corner and section corner were found, in accordance with the township plat, at the northwest corner of Sec. 25, T. 65 N., R. 2 W., just east of the small creek that drains a series of lakes to the south. These corners seem to be properly located. To the east along the shore of South Lake about 1,400 paces is another meander corner, evidently intended to mark the intersection of the range line with South Lake. South of this meander corner 333 paces an east-west blazed line was found, but no corner could be located. Continuing south to Dunn Lake, a meander corner was found 250 paces east of the line paced south from the meander corner on South Lake. When the attempt was made to adjust maps based on the land survey to the highly accurate boundary survey, further difficulties encountered at this point showed conclusively that the corners noted above were not properly located. According to the boundary maps the range line should be very near the east end of South Lake if the northwest corner of Section 25 is correct. The probability is that these townships overlap each other on account of inaccuracies in the survey in other portions of the region, mainly, it appears, in T. 65 N., R. 1 W. The maps in this report represent the best compromise possible without a new land survey. Only a complete resurvey of these townships will unravel this tangle.

Surface features.—The topography of this township is essentially like that of T. 65 N., R. 3 W., with which it is continuous. The main feature is the prominent ridge between Gunflint, North, and South lakes on the north and the higher series of lakes on the south, Crab, Mayhew, and Bush. The east-west trend of the lakes, which coincides with the strike of the slate and diabase sills, is very marked. The difference in elevation between the boundary lakes and those to the south is noteworthy. The glacial drift is thin in most of the township except in Sections 19, 20, and 25 and the northern part of Section 26, where irregular terminal moraine covers much of the rock. Elsewhere outcrops are abundant, as is shown on the map.

Geology.—The prevailing formations of the area are alternating diabase sills and slate beds. South of Dunn Lake a prominent dike was traced for some distance, and another at the portage between Birch and Mayhew lakes extends for a mile westward, where it seems to be cut off by the gabbro. The diabase about one-fourth mile south of the northwest corner of Section 26 shows two feldspars; one weathers redder than the other, suggesting the presence of considerable potash.

The large sill that forms the dip slope north of Loon Lake in T. 65 N., R. 3 W., has a highly porphyritic top, and this porphyry can be traced across this township, at least as far as Lake Louise in Section 27, by a line of porphyritic outcrops. At the outlet of Lake Louise is an especially porphyritic phase with anorthosite patches or inclusions. N. H. Winchell[3] has described a similar occurrence in a sill at the outlet of Gunflint Lake, and such phases were observed by the members of the present survey at intervals throughout the Rove slate area in Minnesota.

Small amounts of chalcopyrite were noted in a highly feldspathic phase of the diabase about one-fourth mile east of the northwest corner of Section 32, but otherwise no evidence of mineralization was noted.

The Rove formation in this township consists of an alternation of slaty and graywacke beds without any definite division into stratigraphic units. One of the best outcrops of the slaty phase is at the falls on a small stream that drains Crab Lake into Gunflint Lake. This outcrop also shows rhombic joint blocks with almost diagrammatic regularity, a feature which seems characteristic of the Rove formation in places. Good exposures of contact-metamorphosed slate occur at intervals along the gabbro contact.

The Rove formation is bounded on the north between Gunflint and North lakes by the Gunflint iron formation. Outcrops of the contact were not observed, presumably because the contact is in the swampy area between the lakes. Good outcrops of the Gunflint formation occur on the shores of North Lake.

Township 65 North, Range 1 West

Locations.—The locations in this township are fairly accurate with respect to topography, as the numerous lakes provide frequent checks. Many discrepancies were found between the town plat and corners actually located. The difficulty between Dunn and South lakes on the west range line has been discussed in the description of T. 65 N., R. 2 W. A somewhat similar difficulty with the land survey was met with at the east range line from the east end of Daniels Lake to the small stream that marks the international boundary between Rove and Rose lakes. This affects the sections to the east to a greater extent and will be referred to more specifically in the description of T. 1 W.

[3] N. H. Winchell, *Final Report of the Minnesota Geological and Natural History Survey,* 5:66.

The accurate survey of the international boundary shows that the meander survey of the Minnesota shore of the boundary lakes was very poor. The pronounced northward projection of Section 21 into Rose Lake, for example, is not shown on the town plat.

Numerous meander corners were found in this township, as shown on the map. The old section corner posts generally had been destroyed by severe forest fires that passed over much of the area.

Surface features.—This township is one of considerable relief, and the topography is irregular as compared with areas of the Rove slate both to the east and the west. In spite of the fact that the geology at certain important points is obscured by surficial deposits, the irregularity shown especially by the lakes is believed to be a result of geologic structure. The prevailing topography consists of steep north slopes and gentle dip slopes to the south. Locally, as for example at the portage between Duncan and Moss lakes, a north-south dike forms a prominent ridge.

Glacial drift is not particularly abundant in this township except in the southern part of Section 31. Diabase exposures are abundant, but slate exposures are usually small and are almost entirely confined to the north-facing bluffs. The difference in elevation between the boundary and the more southerly lakes is well brought out by the stairway portage, with a drop of 139 feet between Duncan and Rose lakes.

Geology.—The sills of this township are mainly normal diabase but a few unusual phases occur locally. At the southwest end of Partridge Lake on the line between Sections 30 and 31 is a prominent hill or ridge of porphyritic diabase. This occurrence suggests a dike. The dike at the portage between Duncan and Moss lakes was noted above. The structure here is not entirely clear, but the dike seems to pass into a sill southward along the shore of Moss Lake. The diabase of the ridge is porphyritic with small phenocrysts of plagioclase. Near the shore, included in the normal phase of the diabase, is a very coarse diabase grading to anorthosite. The masses are often rounded. Single crystals of feldspar up to three inches in length were also observed. The rounded masses of anorthosite vary from a few inches to several feet in diameter.

The diabase just north of the meander corner between Sections 25 and 26 on the north shore of Daniels Lake is impregnated with red feldspar and grades toward the usual red rock (granite). This is the westernmost occurrence of a granitic phase of the Logan sills found during the work. The diabase between Hungry Jack and Bearskin lakes also contains some reddish feldspar and probably hornblende.

The Rove formation that outcrops in this area is an alternation of slate and graywacke beds that perhaps contain more than the average amount of graywacke and quartzite. The graywacke beds and thin diabase sills so much resemble each other in the field that thin sections were necessary to decide the classification in places. This resemblance was noted particularly of the diabase on the south side of Daniels Lake.

A good exposure of slate exists in the steep bluff in NW¼ Sec. 21 near the western section line. The slate is thin-bedded and stained yellow and brown by the weathering of pyrite. About 6 inches of the slate is metamorphosed to a dense hornfels at the lower contact of the thick sill that forms the bluff. The slate exposures in the township as a whole are disappointingly small, the diabase talus usually covering up the slate at the foot of the bluffs.

Because of scanty outcrops considerable interpolation has been necessary in mapping the slate belts; for example, the topography at Partridge Lake strongly suggests the presence of a belt of slate, though no exposure was found.

The only evidence of mineralization, aside from a little pyrite, occurs in an old exploration pit a few paces from Moss Lake on the portage to Hungry Jack Lake, where an old hearth still remains. A pit was sunk on a calcite vein in diabase. The extension of the vein cannot be followed because of the cover of glacial drift. There is no evidence that any metallic minerals were discovered in the course of the work. This calcite vein is the westernmost of the several large veins found in the Rove slate area. Veins of this type are more abundant in the region near Pigeon Point.

Township 64 North, Range 1 West

Locations.—As the map of this township shows, comparatively few section and meander corners were found. Almost the entire area has been burned over and the corners have been destroyed. The original land survey seems to have been very poor, for several discrepancies were found in the cases of such corners as were located. Only a complete resurvey by the land office will straighten out these difficulties. The discrepancies were particularly troublesome in the vicinity of Aspen Lake. The traverses made during the geological work indicated that the meander corner near the northwest end of Aspen Lake is but three-quarters of a mile from the east line of Section 11. It is probably a mile and a quarter from the meander corner on Aspen Lake to the west line of Section 10. The corners and outlines of Flower and East Bearskin lakes seem to be approximately correct.

We were informed that much search by owners and by the United States Forest Service men had failed to locate a single original corner along the north town line of this township. An attempt has been made to adjust the discrepancies on the maps in this report in a reasonable manner.

Surface features.—The topography of this area is rolling, with a pronounced knob and sag effect in many places as a result of considerable deposit of terminal moraine. The moraine also accounts for the relative scarcity of outcrops over parts of the area. The Duluth gabbro forms a pronounced bluff along the southern boundary of the Rove slate area, especially in the eastern part of the township.

The morainic belt is shown by Leverett[4] as moraine of the Lake Superior lobe. The weathered condition of some of the drift and gabbro outcrops suggests that possibly some older drift remains uncovered.

Geology.—The scarcity of outcrops in many places in this township has made necessary considerable interpolation in mapping the slate and diabase areas, and the map must therefore be considered as somewhat generalized.

The Rove formation is as usual an alternation of graywacke and slaty phases. Near the Duluth gabbro across the entire township the slate is considerably metamorphosed in the manner described in the general section on contact metamorphism. The gabbro contact swings sharply, thus transgressing a considerable horizon of slate that seems to maintain an east-west strike.

An upper contact of a sill with slate which was observed at the east end of Hungry Jack Lake in NE¼ Sec. 2 furnished one of the few opportunities to observe the phenomena exhibited by this contact. The exposure is on a ridge between two bays with a dip slope to the south of about 18°. The slate locally is quartzitic and is much crumpled and contorted. The crumpling seems to be characteristic of the upper contact and was not observed at the lower contact of the sill, which is found across the bay a short distance to the south. Similar crumpling was noted in remnants of slate on top of a sill on the north shore of Flower Lake in Section 1.

In Section 6, south of Flower Lake, a series of small step faults offset the slate on the east side of the point. The strike changes from N. 70° E. on the west to N. 60° W. on the east. The diabase as well as the slate is faulted, and the largest displacement determined is about 8 feet.

The diabase intrusives are about normal in most of the township. A sill south of Aspen Lake in Section 11 is conspicuously porphyritic with a tendency to glomeroporphyritic texture in places. In Section 10 a red rock (granite) differentiate lies above the porphyritic phases and grades into them. A similar differentiate occurs also in small amounts in the top of a sill near the northeast corner of Section 12.

No veins or prospects suggestive of mineralization were noted in this area.

Township 65 North, Range 1 East

Locations.—Locations in this township, like those to the west, are uncertain in some places because of an inaccurate original land survey and because forest fires have destroyed the marks of the original survey. Serious discrepancies in the original survey in two places require special mention. One is in Sections 19 and 30. The town plat shows the international boundary along the portage from Rove Lake to Rose Lake. The boundary survey follows the small creek that drains Rove Lake into Rose Lake; and as this bends southward to the north line of

[4] Frank Leverett, *Moraines and Shore Lines of the Lake Superior Region* (Professional Paper 154 A, 1929), Plate 1.

Section 30, Section 19 is almost nonexistent. Daniels Lake is shown on the town plat as extending almost to the east line of Section 20, whereas as a matter of fact it extends little more than a quarter of a mile into that section. The finding of both meander corners and section corners on the fourth principal meridian, which forms the west range line of the township, makes it certain that the map in this report is approximately correct in that respect.

The second discrepancy is between the corners on part of Clearwater Lake and those on the western part of Caribou Lake. It seems evident that they were located without surveys between. In general the corners on the two lakes seem to be offset about 250 paces with respect to each other. Caribou Lake apparently extends about one-fourth mile farther west than the town plat indicates, and it is shown thus on the maps of this report. The east end of Caribou Lake is also incorrectly shown on the town plat, from which Little Caribou Lake is omitted. Other irregularities of a less serious nature were encountered on Clearwater Lake farther east.

Surface features.—This township is an area of considerable relief, varying from an elevation of approximately 1,489 on Pine Lake in the extreme northeast corner to slightly over 2,000 feet south of Clearwater Lake and on the ridge between Clearwater and Rove lakes. The northward-facing bluffs overlooking Clearwater, Rove, and Mountain lakes are from 300 to 400 feet in height, and vertical cliffs 100 feet high are not unusual. (See Figure 25.) It is probable that the main sills of each of these divides are rather thick, and that this thickness accounts for the relief. The pronounced east-west trend of the topography is evident and suggests a simple east-west trend of the slate beds and sills.

Glacial drift is relatively thin over most of this township, as the almost continuous outcrops in many areas show. Sections 19 and 30, between Clearwater and Rove lakes, show some typical morainic topography, as do Section 27 along the shore of Clearwater Lake and Section 32 west of Caribou Lake.

Geology.—The major feature of the geology of this township is the presence of two large sills that form the ridges between the larger lakes. These sills are probably somewhat thicker than average but show few unusual features. As seems often to be the case in the Logan sills, the big sill south of Clearwater Lake is decidedly porphyritic, with plagioclase phenocrysts and anorthositic patches. On the center line of Section 34, about one-fourth mile north of Caribou Lake, is a good exposure of red rock with pegmatitic stringers. On the steep north-facing bluffs smaller sills are usually found in the slate and graywacke. Along the shore of Rove Lake in Section 22 are outcrops and talus of reddish diabase, apparently the chilled top of a sill.

The good exposures of slate and graywacke along the bluffs overlooking Rove Lake have given the formation its name, which seems to have been first used by Clements[5] in his Vermilion monograph. The formation as exposed on Rove Lake consists of the usual alternations of slate and graywacke phases and is typical of the greater portion of the formation as exposed in Minnesota.

Veins or other indications of mineralization seem to be lacking in this township.

The exposures of graywacke near the range line on the east side of Section 25 and south of the outlet of Clearwater Lake show remarkable examples of jointing. (See Figure 8.) Not only are the usual rhombic pieces found here but also polygonal columns very closely resembling columnar jointing in basalt. Ripple marks were noted in slate outcrops near the east quarter corner of Section 22.

In some places, notably along the south shore of Clearwater Lake in Section 28, the graywacke phases of the Rove formation and the thin diabase sills so closely resemble each other that thin sections are necessary to identify them.

Township 64 North, Range 1 East

Locations.—Aside from some confusion between the section lines and the outlines of the lakes in this township and those in the township to the north around Caribou Lake, the town plat of the original land survey was found to compare very well with section and meander corners as they were found in the field. The outlines of the lakes also were found to be correct in all essential respects. The map accompanying this bulletin shows several small lakes and ponds not crossed by a surveyed line that are not shown on the town plats.

Surface features.—The general east-west trend of the lakes and ridges in this township is comparable with conditions in the townships to the north and east. There is a well-defined tendency for the lakes to develop long arms or bays at the ends, as East Bearskin, Alder, Flower, Sucker, and Canoe lakes exemplify very well. This is a result of the pinching out or narrowing down of the diabase sills which form the ridges that divide the lakes. An unusually diagrammatic saw-tooth ridge forms the point at the west end of Alder Lake. (See Figure 3.)

The Duluth gabbro forms a continuous east-west bluff across the township, facing north toward the slate area. The sills and consequently the saw-tooth ridges are much smaller than in the township to the north. They seem, in fact, to be rather generally smaller along the southern border of the formation, where it is adjacent to the Duluth gabbro. The drainage of the area is mainly to the east into Pine Lake, part of the water going by way of Pine River and part by way of Caribou Lake to the north.

Geology.—The Duluth gabbro and associated metamorphosed slates are unusually well exposed in this township, and the contact meta-

[5] J. M. Clements, *The Vermilion Iron-bearing District* (United States Geological Survey Monograph 45, 1903).

morphism of the Rove formation may be studied here to better advantage than elsewhere with the possible exception of the township to the east. The gabbro and the metamorphic zone show several of the pegmatites and aplites of siliceous material which Grout[6] has described as more or less characteristic of the base of the lopolith.

The contact metamorphism of the slate is described in detail in Part I of this study, pages 33 to 35.

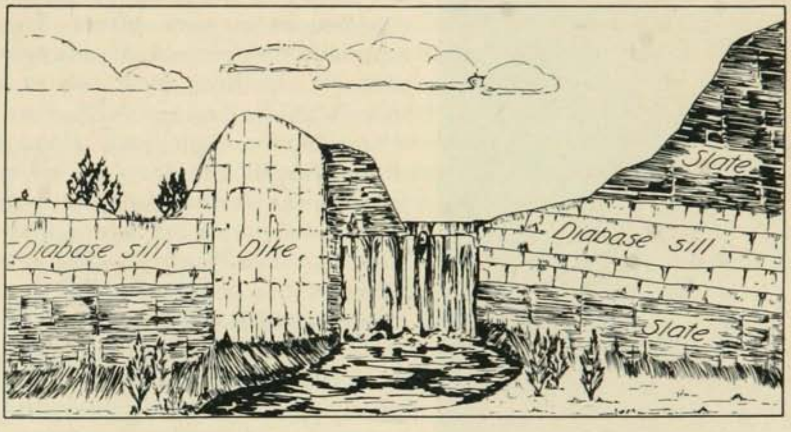


FIGURE 38. — Sketch showing relation of slate and diabase at Pine River Falls, Sec. 1, T. 64 N., R. 1 E.

South of Alder Lake the dip of the slate seems to flatten near the gabbro, whereas in general it steepens, as may be observed on the cross sections. (See Plates 16–19.) The sills in this area are for the most part normal diabase. Small exposures of red rock were noted in the northwest corner of Section 7, on the point in Alder Lake in Section 10, on the south shore of Rocky Lake in Section 3, and on the north shore of Canoe Lake on the line between Sections 1 and 2. Where the relations of the granite to the diabase are clear, the granite appears at the top of the sill, in some places apparently grading into diabase and in others more sharply set off from it. With the red rock on the point in Alder Lake were small inclusions of anorthositic diabase.

Pine River is formed by two small streams that flow out of Canoe and Rocky lakes, respectively, and unite in a small beaver pond in NE¼ Sec. 2. The stream flows through other ponds toward the east; then in the northwest corner of Section 1, just west of the center line, it cuts through a low ridge formed by a small sill. The gorge formed by this stream exposes the rocks and their relations unusually well.

The river flows over two falls, each formed by a diabase sill overlying slate and graywacke. (See Figures 39 and 40.) Veins in the diabase con-

[6] F. F. Grout, "The Pegmatites of the Duluth Gabbro," *Economic Geology*, 13: 185–197 (1918).

tain calcite and sulphides. They follow slickensided surfaces, indicating the presence of faults. The slate dips 13° S. above the upper falls and 32° S. below the upper falls, where it is obviously disturbed. The relations at the lower falls are shown in Figure 38. Here the diabase dike cuts both slate and diabase sill and the slate and sill are offset. The shear zones and dike strike N. 80° W.

FIGURE 39. — Diabase above slate at Pine River Falls, Sec. 1, T. 64 N., R. 1 E.

Jointing in the slate and diabase is conspicuous in some places. It was especially pronounced in a graywacke phase of the Rove formation on the shore of Alder Lake in NE¼ Sec. 11, where most of the rock along the shore was in the form of rhombic joint blocks varying from an inch or two across up to a maximum of about two feet. (See Figure 7.) The normal strike of the bedding in the slate is about N. 80° E. with about a dip of 15° S. Some of the bluffs of diabase near Rocky and Canoe lakes show almost perfect vertical faces up to 75 feet high and continuous about due east and west for considerable distances. These cliffs seems to be a result of very prominent east and west joints in the massive diabase. Similar joints were observed south of Fanny Lake in the township to the east.

Faults are uncommon in the Rove area, if we may judge by the outcrops. A small one was noted in NW¼ Sec. 7, where diabase overlies well-bedded quartzite and both are offset about 6 feet with development of considerable breccia.

Except for the calcite veins at the falls in Pine River no evidence of mineralization was noted in this township.

TOWNSHIP 65 NORTH, RANGE 2 EAST

Locations. — Very few section or meander corners were found in this township. Practically the entire area has been burned over and the original corners have been destroyed. The only serious discrepancy found in mapping was an apparent offset between corners on West Pike and Pine lakes, which were supposed to be on the same line. The corners on Pine Lake seem to be about one-eighth of a mile west as regards those on the south side of West Pike Lake. Sections 20, 21, 28, 29, 32, and 33 are shown of extra width. This adjustment was necessitated in fitting the mapping of the geological survey and the land survey to the very accurate international boundary maps. The adjustment as made would probably be modified if the township were resurveyed by the land office. It is somewhat doubtful whether the sections noted above are actually of extra width as shown, but this amount of error exists in the land survey somewhere in this vicinity.

Surface features.—The general east-west trend in this township, with unusually broad ridges between lakes, is continuous with that of the township to the west described above. It is noteworthy that a break in this trend may be observed in the northeast sections, where the topography is that of a somewhat dissected broad plateau. This, as will be shown below, is an expression of a local change in structure.

Glacial drift is decidedly thin over most of the township. The effect of the glacier seems to have been to scour off the diabase ridges and to some extent dump the material in the valleys, thus forming dams that hold back the lakes and ponds. The southern boundary of the township is formed entirely by Pine Lake, the largest of the many east-west trending lakes of the Rove slate area. The dip slope between the bluffs overlooking West Pike Lake and the shore of Pine Lake is particularly uniform.

Geology.—The major features of the township are the two large sills that form the main east-west ridges. In the western portion of the township these sills are very thick, but toward the east they seem to break up and are probably complicated by secondary structures.

The main sill between West Pike and Pine lakes forms an unusually regular dip slope in Sections 32 and 33, and the top of the sill is decidedly porphyritic. Near and along the shore of Pine Lake anorthosite patches are abundant. These patches seem to represent clusters of the phenocrysts of the porphyry. Phenocrysts up to three inches in length were observed, the largest usually occurring near the anorthosite patches. The sill north of West Pike Lake, though large, seems to lack porphyritic and anorthositic phases, which suggests a primary difference in the composition of the magma that formed the various sills. This idea receives further support from the observation of

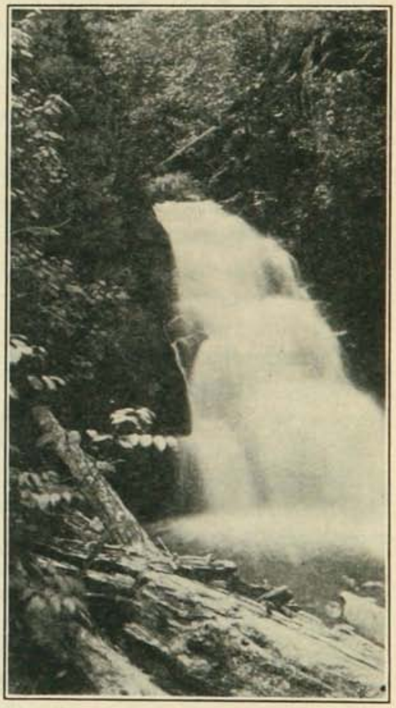


FIGURE 40.—Pine River Falls, Sec. 1, T. 64 N., R. 1 E.

a composite sill one-fourth mile west of the center of Section 3 and at intervals to the eastward. The base of the main porphyritic sill is intruded by a reddish sill apparently of later date; but in other places the diabase apparently grades into an intermediate type of rock and finally into red rock or granite.

Considerable weathering of diabase was noted along the cliff that faces Little Caribou Lake at the east end. The depth of decomposition was so great that it was concluded that the cliff had escaped the full scouring action of the glacier.

A decided break in the prevailing structure of the area is indicated in the northeast part of this township, particularly in Sections 23, 24, 25, and 26, where lakes and drainage cross the prevailing strike and long north-south exposures of slate show an unusually low dip or horizontal beds. This variation is clearly shown in the cross section on Plate 18. To the south near East Pike Lake the normal dip prevails. This structure is described and interpreted in the general discussion of structures, on page 14. The slate in this area shows few unusual features. The graywacke phases greatly predominate, but thin slaty beds are not uncommon. Unusually conspicuous jointing of the graywacke into rhombic blocks was noted on the shore of Mountain Lake in Section 19.

Some exploration for ore has been carried on in this township, but results have been disappointing. Near the shore of Pine Lake, in SE¼ Sec. 31, a pit exposes fragments of a slate breccia cemented with calcite. A similar breccia is exposed in a pit very close to shore just east of the meander corner between Sections 31 and 32 on Pine Lake. This is evidently the work referred to by Winchell,[7] who noted that the gangue was principally calcite and quartz, with some pyrite, galenite, sphalerite, and chalcopyrite.

Township 64 North, Range 2 East

Locations.—The entire area of this township that is underlaid by the Rove slate and associated formations has been burned over at least once, with the result that nearly all marks of the original section and meander corners have been destroyed. In general no serious discrepancies were found between the town plat and conditions in the field. Corners on the north side of Pine Lake aided materially in locating the approximate position of the section lines south of the lake. Sections 4, 5, 8, and 9 are mapped of extra width in conformity with the township to the north, where the adjustment was necessitated by the accurate survey of the international boundary.

Surface features.—The pronounced east-west trend of the ridges and lakes as usual expresses the prevailing structure of the slate area. The Duluth gabbro as a rule forms a high plateau-like area, with a northward-facing bluff along the south border of the Rove area.

[7] N. H. Winchell, Seventh Annual Report of the Minnesota Geological and Natural History Survey, 1878, p. 21.

The narrow ridges of this area suggest that the sills are much thinner than north of Pine Lake. As noted previously, this seems characteristic of the sills near the gabbro contact. Since glacial drift is thin or lacking over most of the area, outcrops are even more abundant than usual. The very pronounced rise in elevation all long the south shore of Pine Lake is a result of a group of small to moderate-sized sills, one close above another.

Geology.—A series of comparatively small sills alternating with slate and graywacke is characteristic of the township. The Duluth gabbro forms the south boundary of the Rove area, which here shows conspicuously the contact metamorphism which is referred to in Part I of this report. One of the best exposures for study of the contact is at the bluff on the south shore of Stump Lake in the eastern part of Section 12.

The diabases of the sills are mainly normal, lacking conspicuous porphyritic phases such as are found to the north of Pine Lake. Small outcrops of red rock (granite) at the tops of sills were noted in Sections 1, 2, and 11 on the shores of Stump Lake, as was some rock intermediate between diabase and red rock. This is a strong indication of the relation of the latter to the diabase sills.

The Spalding mine, as it is locally known, consists of a series of pits and shafts on the south shore of Lake Miranda in Section 5. N. H. Winchell gives considerable data on this work in the Seventh Annual Report of the Minnesota Geological and Natural History Survey, pages 18 to 21. The work has been long abandoned. The exploration is spread along the south side of the lake for nearly half a mile and seems to have opened a shattered zone running nearly east-west. The bluff at the west is diabase to the water's edge, but slate probably was encountered in the shafts. Farther east the workings probably started in slate. The shattered zone passed through both the diabase and slate. The cement of the breccia is quartz and carbonate—probably some iron carbonate, since the material is now rusty. Disseminated pyrite occurs in the diabase only. Winchell reported the vein as 6 to 8 feet wide. Mr. Spalding reported traces of native silver, but none has ever been observed by either Winchell or members of the present survey. The location had been thought to be the site of ancient diggings, but Winchell considered that improbable.

Township 65 North, Range 3 East

Locations.—Considerable difficulty was encountered in getting proper locations in this township, since most of the original stakes had been destroyed by fire and the outlines of the lakes differed widely from those shown by the plat. The most marked discrepancy is at the east end of East Pike Lake, which is shown on the town plat as extending past the middle of the section, whereas in fact it does not extend more than 200 yards east of the west line of Section 28. The map given here is based largely on the international boundary survey, which was used also as a control for the traverses made during the field work.

Surface features.—The western part of this township is essentially a continuation of the topography of the township to the west. To the east the township under consideration is cut off by North Fowl Lake of the international boundary. The presence of a lake with so long a dimension north and south is an unusual feature in the Rove slate area. It seems to be accounted for by a well-defined change in the strike from east-west to northwest-southeast. This change is noted also to some extent in the township to the south, although it is not so pronounced as in this area. The change in trend is local, for farther east the prevailing strike is about east-west.

Glacial drift is not especially thick over this area, but north and east of East Pike and John lakes it is abundant enough to make the outcrops rather scarce. The Rove formation is continuous beyond North Fowl Lake in Canadian territory.

Geology.—The diabase intrusives of this township are normal in character and exhibit no unusual phases worthy of description. The alternation of sills and slate is unusually well shown in Section 32 south of East Pike Lake, where at least four sills crop out within about a half mile in a north-south direction.

The Rove formation exposed in this township is the normal alternation of graywacke and slate, the former predominating along Moose Lake and the latter south of East Pike and John lakes. At the bluff on the west shore of John Lake in Section 33 certain layers of the slate appear to be siliceous and show an öolitic texture very much like the greenalite granules of the Biwabik formation. This exposure of slate is one of the most extensive in the entire area mapped; in one place a vertical exposure of 165 feet was estimated from barometer readings. It is all thin-bedded.

A fault of rather more than usual offset was observed on the bluff overlooking North Fowl Lake, just west of the east section line and 500 paces north of the southeast corner of Section 27. (See Figure 11 C.) The bluff exposes only diabase for half a mile to the west. Slate is exposed along a vertical contact with diabase from an elevation of 1,550 to 1,590 feet, where diabase overlies the slate. The throw of the fault is thus undetermined, but it is over 40 feet. The slate is much crumpled and folded. The broken slate and diabase are somewhat pyritic.

A fault was observed also along the north-south cliff near the center of Section 30. The fault strikes east-west, and the upthrow is about 10 to 15 feet on the north side.

No evidences of mineralization or veins were noted other than a little pyrite at the fault described above.

Township 64 North, Range 3 East

Locations.—Very few section and meander corners were found in this township, mainly because of the very severe forest fires which have swept over much of it. In general, locations were fairly satisfactory, although some pronounced discrepancies were found between the town plat and conditions in the field. Such discrepancies were especially noteworthy at the east end of Pine Lake, which is shown on the plat as extending nearly across Section 5, whereas the meander corner between Sections 5 and 6 shows clearly that the lake extends but slightly over one-fourth mile into the section. Most of Royal Lake shown on the map is now swamp and rice beds. Portage Brook is shown on the plat as a stream coming out of the small lake south of Stump Lake and flowing across the township south of and more or less parallel to Stump River. What is apparently the upper part of this creek is actually a branch of Stump River, and the lower part, now known as Otter Brook, drains Otter Lake south of the area mapped.

Surface features.—This area is by far the most complex in its topography of the townships considered thus far. The simple east-west-trending saw-tooth ridges break up east of Pine and McFarland lakes, although one major sill continues east to the outlet of South Fowl Lake and beyond into Canada. This ridge is one of the most mountainous in appearance and is the barrier that backs up the water of North and South Fowl lakes, which were raised much higher in the past by a logging dam. A series of rapids and falls is formed where the Pigeon River breaks through this high ridge in a narrow gorge.

The Duluth gabbro, which forms the southern boundary of the slate area from Gunflint Lake to Stump Lake, takes an abrupt turn to the southeast in Section 7 and ends as a sill-like projection in Section 27. A tongue of Keweenawan flows separates the gabbro from the slate from about the center of Section 21 eastward. The pronounced northward-facing bluff that borders the slate area is, however, continued eastward by the basal conglomerate, by sandstone, and by overlying flows of Keweenawan. The valley of the Stump River forms the longest relatively flat area in the entire Rove area in Minnesota. Outcrops are scarce in this flat swampy area, but it seems safe to assume that it is underlaid mainly by the slate.

It is perhaps worthy of note that the valley of the Stump River is by far the largest area unbroken by lakes between Gunflint Lake and the Pigeon River. It is likewise the most level region in the area mentioned. This large swampy area is shown by Elftman [8] and by Leverett [9] as part of glacial Lake Duluth. According to Elftman, a lake, which he called Lake Omimi, existed here before the ice retreated beyond Grand Portage Bay. The old shore lines were not observed during the present work; and Elftman notes that they are not definitely marked.

Geology.—It is noteworthy that the slate of this area has none of the pronounced contact metamorphic zone which is commonly present farther west, where the gabbro lies on slate. The almost diagrammatic

[8] A. H. Elftman, "The Geology of the Keweenawan Area in Northeastern Minnesota," *American Geologist*, 21:90–109 (1898).

[9] Frank Leverett, *Moraines and Shore Lines of the Lake Superior Region* (United States Geological Survey Professional Paper 154 A, 1929), p. 1–71.

alternation of large sills and slate breaks up in this area, and while sills are still important, they lose their regularity and the structure is more complicated. In the valley of the Stump River and around Royal Lake outcrops are not abundant enough to make accurate plotting of the structure possible, and no attempt has been made to draw in the complete belts of slate and diabase. It is evident that the strike of the slate and sills swings southward somewhat in conformity with the Keweenawan contact.

A very unusual structure so far as the Rove area in Minnesota is concerned occurs in a hill in the southern part of Section 10 and the northern part of Section 15. On the north side slate outcrops beneath a diabase cliff in the normal relation for the region, but on the south side of the hill the dip is north. This seems without doubt to be a synclinal structure with the pitch to the west. Local drag folds and minor faults are associated with this structure.

The fine-grained graywacke at the outlet of Pine Lake in Section 6 has a minute but perfect cross-bedding. On the Stump River in Section 24 a sandy phase of the graywacke shows a peculiar irregular jointing that at first sight may be confused with bedding. (See Figure 21.) This structure, which was observed in other places farther east in the course of later work, is one of the unusual phases of the Rove formation.

The diabases of this area are mainly normal; porphyritic phases are uncommon, as might be expected in the smaller sills. A very coarse porphyritic phase with anorthosite inclusions was, however, observed on the prominent hill a short distance north of the center of Section 13. This is very much like the occurrences noted on the north shore of Pine Lake. With the anorthosite inclusions were unusual fine-grained slaty inclusions. A porphyritic diabase was also observed on the high hills south of McFarland Lake in Section 9.

Considerable red rock (granite) was observed with the diabase north of the gabbro in Sections 15, 16, and 17.

On the south shore of Long Lake in Section 7 a composite sill was noted that graded from porphyritic to dark basic to reddish material. A distinct banding was noted in the several phases. This formation is probably a continuation of that noted in Sec. 11, T. 64 N., R. 2 E.

A noteworthy change along the southern border of the Rove formation occurs in this township. The Duluth gabbro forms the southern boundary and overlies the Rove all the way from Gunflint Lake to Section 22 in this township, where the sill-like extension of the gabbro lenses out in the Keweenawan flows. Near the end the gabbro is separated from the slate by basalt flows and the basal conglomerate and sandstone of the Keweenawan. One of the very few outcrops of the Puckwunge conglomerate occurs in Section 22. The Keweenawan sediments and flows form the southern boundary of the Rove formation from this township to the islands south of Pigeon Point in Lake Superior.

Considerable exploration has been carried on at a prospect on the shore of McFarland Lake in Section 5. The mineralization is along a shear zone where slate has been faulted down against diabase. The relative movement is clearly shown by the drag of the slate. The chief minerals of the vein are calcite and quartz, with much chlorite, a result of alteration of the diabase and slate. Much of the dump is chloritic slate and slate breccia with a quartz-calcite matrix. The slate strikes N. 70° W. and dips 20° to 25° S. The fault zone can be traced a short distance east and west and is well exposed in a small creek bed about 300 feet west of the shaft. The strike of the fault appears to coincide with the strike of the bedding. This is probably the vein referred to by Winchell in the Seventh Annual Report, page 20, where he notes the occurrence of pyrite, galena, and native silver.

Along the south side of Pine River, just below the outlet of John Lake, are outcrops of brecciated diabase with much coarse calcite, quartz, and some pyrite. The diabase is much altered and slickensided with chlorite. In one place the diabase was observed to transgress the bedding of the slate diagonally for a distance of 6 feet. This was apparently not a post diabase fault, for the diabase was dense all along the offset, as if chilled. (See Figure 11 D.) Similar transgression on a somewhat larger scale was noted also on the big bluff in NE¼ Sec. 10, where the slate was cut across by the diabase for fully 25 feet.

About 200 feet south of the dam at the outlet of South Fowl Lake on the Minnesota side of the Pigeon River is a small exploration pit on a calcite vein. The calcite occurs along fractures and has apparently replaced the diabase as masses. One mass as exposed in place is about 1 x 2 x 2 feet. A short distance north of the dam on a bluff overlooking the lakes a later dense diabase dike cuts across the usual coarse diabase. This later intrusive is very rarely found in the Rove area of Minnesota.

Winchell[10] reported the occurrence of two veins in Sections 9 and 10 of this township. They contained quartz and brecciated quartzite and occupied faults between slate and trap. These were not discovered in the present work.

Township 64 North, Range 4 East

Locations.—The map shown here is based on the international boundary map of the Pigeon River. The only land survey corners found are the meander corners between Sections 26 and 27, the section corner on the river bank at the north end of the line between Sections 35 and 36, and several resurvey corners in the northeast part of Section 36. With these corners as a base the boundary map was tied to the town plat as well as possible, but the original land plat is hopelessly inaccurate along the river.

To adjust for unavoidable discrepancies, in the map of this township the section lines have been arbitrarily offset along the west range line

[10] N. H. Winchell, Seventh Annual Report of the Minnesota Geological and Natural History Survey, 1878, p. 20.

with respect to T. 64 N., R. 3 E., so far as section lines are concerned. The topography will be found to fit accurately following the boundary survey. The western tier of sections are shown on the town plat as only one-fourth mile wide, whereas according to the boundary maps they should be about three-fourths of a mile wide.

Surface features.—The topography of the Rove area in this township is very simple. The Pigeon River has cut a broad flat valley, presumably in slates. On the south, high bluffs of the Keweenawan escarpment overlook this valley except where the Kameskeg River has eroded a broad valley at right angles to the Pigeon River. A single large sill of diabase overlying slate forms a characteristic ridge in Sections 19, 20, 28, and 29. The broad swamp along the river was occupied by an arm of Glacial Lake Duluth as noted in the previous chapter.

The broad swampy flats are unusual for the Rove slate area, and the complete absence of outcrops suggests a rather deep alluvial deposit along the river. The valley, which is very large for the present stream, was doubtless formed in glacial time, and the alluvial deposit was formed as the abundant waters of the period gradually receded. Much of the deposit may have been formed by deposition in the glacial lake shown by Elftman[11] as occupying this valley when the ice was retreating.

Geology.—Aside from the prominent sill that extends from Section 19 to Section 28, the principal outcrops are Keweenawan rocks along the south side of the valley. The bluffs usually expose a white quartzose sandstone overlaid by basalt flows. The contact of this sandstone with the slate below is nowhere exposed, but on the dip slope of the sill in the northeast corner of Section 30 is an outcrop of conglomerate lying directly on diabase. This is interpreted as an outlier of the basal Puckwunge conglomerate that has not been eroded from the dip slope of the diabase sill.

A typical sill of diabase with slate exposed on the north side occurs in the northeast corner of Section 36 and the small adjacent fraction of Section 25. This is apparently an erosional outlier of a large sill.

No veins or other evidence of mineralization were noted in this township.

Townships 63 and 64 North, Range 5 East

Locations.—The Rove formation extends only into the northeast corner of T. 63 N., R. 5 E. This small area forms an integral part of the structure of the main area, and so it is shown on the same map with T. 64 N., R. 5 E., and the two are discussed as a unit.

These two townships were included in the old Grand Portage Indian Reservation and were resurveyed by the General Land Office in 1916 and 1917. In the resurvey all section corners and many forty corners as well were marked by iron stakes. The locations shown on the accompanying map are therefore accurate and will be found to check closely

[11] *Op. cit.*

with the town plat. The corners found are not marked on the map since practically all are in place.

Surface features. — The topography of the two townships contrasts sharply with that of the Rove area from Gunflint Lake to North and South Fowl lakes. Lakes are absent, and the prevailing east-west trend of the topographic features is broken by transverse ridges. Inasmuch as the topography in both regions developed under preglacial stream erosion and was modified by glaciation, the differences must be the results of different geologic structure.

FIGURE 41. — Partridge Falls, Pigeon River. Formed by dike of diabase in slate.

The southern boundary of the Rove formation is like that in T. 64 N., R. 4 E. A prominent northward-facing bluff is formed by basalt flows overlying Keweenawan sandstone. In front of the bluff there is normally a swamp in which the unconformity between the Keweenawan and Huronian is buried.

The prevailing topography consists of ridges trending in general east and west. Some of these ridges have steep northward-facing bluffs with a gentle dip to the south, clearly a result of erosion of a sill in the slate. Other ridges are steep on both sides, in which case the underlying structure is clearly that of a dike. Many of the dikes trend in a general east-west direction, but several are diagonal to the prevailing trend.

The highest altitude in this area is on the high ridge near the quarter corner between Sections 36 and 1, where the uncorrected barometer reading was 1,720 feet above sea level. This is 1,100 feet above Lake Superior, which is only three miles distant.

The Pigeon River, which flows in the broad flat valley forming the north boundary of T. 64 N., R. 4 E., changes rather abruptly in this township to a swiftly flowing stream with rapids, falls, and gorges. In

Section 30, Partridge Falls (see Figure 41) is the first of several rapids and falls over which the river passes on the way to Lake Superior. Along Section 21 is the picturesque Split Rock Canyon. (See Figure 42.)

A little study of the maps of the townships mentioned above, together with T. 64 N., R. 6 E., suggests that the Pigeon River at one time flowed eastward instead of turning northward just above Partridge Falls. Thus the broad swamp extending from Section 31 to Section 35 may represent the old channel that turned northeastward in Section 35 and flowed down the broad valley indicated by the contours to join the present valley in Section 20 below the International Bridge. Deflection of the river to its present youthful valley from Partridge Falls to the International Bridge probably was due to deposition of glacial drift in the old valley.

FIGURE 42. — Split Rock Canyon eroded in Rove slate, Pigeon River.

In Section 29 is the Pigeon River end of the Grand Portage trail, one of the early avenues of travel within Minnesota.[12] This was the site of Fort Charlotte.

Geology. — As indicated in the discussion of the topography, the structure of this area is much more complex than that of areas to the west. The southern boundary of the area of the Rove formation with the Keweenawan sandstone-basalt escarpment is continuous from the west. The escarpment so continuous in the west has been largely removed by erosion in Sections 1, 2, and 3 of T. 63 N. In Section 3 are exposures of rock that show an important relation between the large diabase dike that extends across Section 2 as well. This dike is clearly intrusive into slate in Section 2 and in Section 3 cuts across the Keweenawan sandstone and basalt flows. This same dike shows other interesting relations in Sec. 36, T. 64 N., where the ridge broadens and then

[12] N. H. Winchell, *Final Report of the Minnesota Geological and Natural History Survey*, 4:502–503; Solon J. Buck, "The Story of the Grand Portage," *Minnesota History Bulletin*, 5:14–27 (1923); and G. M. Schwartz, "The Topography and Geology of the Grand Portage," *Ibid.*, 9:26–30 (1928).

divides with a narrow southerly branch that is clearly a dike in slate and a northerly branch that is without question a sill. This is clear proof that at least some of the so-called Logan sills are Keweenawan in age and later than at least the lower Keweenawan flows. Erosion has cut out much of the slate, leaving a broad amphitheater in SE¼ Sec. 36 that to some extent reminds one of a glacial cirque. Another branching intrusive of similar nature occurs in Sections 34 and 35. Taking the area as a whole, dikes are a conspicuous feature, especially when contrasted with the intrusives in the Rove area farther west, where sills are very abundant and recognizable dikes decidedly uncommon.

In connection with the dikes it was noted that contact metamorphism of the slate is much more conspicuous than at sill contacts, as is noted in Part I, page 27. This is well shown along the dikes in Sections 34 and 35. At some places in this township the dikes occur as pairs with a small slate belt, more metamorphosed than usual, between them. Crumpling of the slate is characteristic of dike contacts.

Partridge Falls is the result of the river flowing over a dike, as has been described and figured by N. H. Winchell.[13] The striking gorge and falls of Split Rock Canyon along the north boundary of Section 21 are due to deep erosion in slate modified by diabase dikes. The sharp bend in the river at the upper end of Split Rock Canyon, known as the Hairpin Turn, is a result of the deflection of the river by a dike.

There are a few occurrences of red rock (granite) with the diabases of this area, but these are not important as compared with the occurrence on Pigeon Point a few miles to the east. These red rocks were observed near the center of Section 26, in NE¼ Section 36, near the center of Section 35, T. 64 N., R. 5 E., and in NW¼ Section 3, T. 63 N., R. 5 E.

The Rove formation of this area is the normal alternation of slate and graywacke. No unusual features were noted except the pronounced crumpling and contact metamorphism adjacent to dikes. Unusually good ripple marks were noted on the flat ledges of slate above Partridge Falls. (See Figures 9 and 10.)

A thin conglomerate in the Rove formation is exposed in a small clearing in the northern part of SW¼ Sec. 26. Inasmuch as this could not be traced along the strike either way, its significance is uncertain.

There is more evidence of mineralization in this map area than in any other in the area of the Rove formation in Minnesota. The exposures observed are, however, small, and general conditions so far as known do not appear especially favorable. The most interesting deposit is opened by a shallow pit in SW¼ SE¼ Sec. 25, T. 64 N., R. 5 E. This is described in detail in the discussion of economic geology. The following are the other veins and evidences of mineralization observed in mapping the area.

[13] N. H. Winchell, *Final Report of the Minnesota Geological and Natural History Survey,* 4:508.

A calcite vein crosses the Pigeon River just below Hairpin Turn in Split Rock Canyon between the artificial log chute and the natural falls. The vein is variable and complex in a shattered zone. The main vein is two feet wide in places. It crosses with little change from the quartzite walls to a diabase dike and up the other quartzite wall of the gorge. There is pyrite and limonite in the walls, but little in the calcite.

In Section 28, just north of the logging road in the northeast quarter of the section, a 6-inch calcite vein strikes N. 10° E. and is about vertical. The walls are graywacke quartzite. It has been reported that galena was found in this vein, but none was observed by the members of the survey. A little oxidized sulphide and quartz are the only minerals besides calcite.

Several veins and prospects are found in Section 35 in addition to the one described in the section on economic geology. In SE¼ SE¼ Sec. 35 a small stream drains the large swamp to the south and east. Where it passes over the diabase dike a small falls and gorge are formed that expose a small vein with calcite, quartz, laumontite, and pyrite.

A calcite vein with a breccia of rhyolite fragments was found in a pit in NE¼ SW¼ Sec. 35. In the northern part of this same forty a test pit shows a sulphide zone in diabase with pyrrhotite and chalcopyrite.

In Section 36 a similar zone of sulphide diabase is exposed on the cliff just south of the beaver pond near the east quarter corner. In the SW¼ NE¼ of the same section, graphitic slate and pyrite were found with rhyolite or red rock. The graphite seems to have been taken up by the red rock in such a way that small bunches occur in the igneous rock without the characteristic form of inclusions.

Township 64 North, Range 6 East

Locations.—The western portion of this township was within the old Grand Portage Indian Reservation and was resurveyed in 1915 and 1916 by the General Land Office. No difficulty was encountered, therefore, west of a line from the Pigeon River near the center line of Section 28 to a point at the southern boundary of Section 34, about one-fourth mile west of the southeast corner. (See the accompanying map.) Corners east of this were found marked in only a few places, but by means of the international boundary map and original town plat, satisfactory locations were obtained.

Surface features.—This township, as well as adjacent portions of T. 63 and 64 N., R. 5 E. and T. 63 N., R. 6 E., forms the nearest approach to mountainous topography to be found in Minnesota. N. H. Winchell aptly described the area in the following words: "The hills that diversify the region are of diabase and gabbro that lift their heads up through the slates which they penetrate, sometimes with perpendicular walls, from 50 to 200 feet above the slates which they cut."[14]

Hills but two miles from Lake Superior rise to elevations above 1,400

[14] N. H. Winchell, *Final Report of the Minnesota Geological and Natural History Survey,* 4:503.

feet, or 800 feet above the lake level. The prevailing trend of the topography is somewhat northeast, with long, high ridges representing dikes and sills. In Sections 27 and 34 a prominent ridge occurs almost directly at right angles to the prevailing trend. This is a great dike which represents the northerly extension of Hat Point in Lake Superior.

This is the first township described that borders Lake Superior, and accordingly it shows new physiographic features. Abandoned shore lines border Wauswaugoning Bay and may be clearly seen along some of the rocky hills adjacent to the bay. Glacial Lake Duluth extended up the Pigeon River valley, and extensive deposits of red lake clay are exposed where the river has cut into the lake deposits. Landslides of considerable magnitude were observed in the clays where they are undercut by the river in Section 23. Although Lake Duluth is mapped up the Pigeon River as far as Moose Lake by Leverett,[15] typical lake deposits are not well exposed above this township.

Geology.—The prevailing structure of this area as revealed by outcrops is rather simple, consisting mainly of northeast-southwest-trending dikes and sills with one major cross dike west of Teal Lake. It should be noted, however, that between the ridges are relatively broad valleys filled with glacial drift and lacustrine clays that rather completely mask the formations beneath. Probably, therefore, the simplicity is more apparent than real. The diabase belts shown on the map doubtless represent only the larger intrusives.

It is worthy of note that the amount of red rock (granite) occurring with the diabase is greater in this township than in any of those to the west. This is doubtless significant in view of the importance of granite on Pigeon Point, immediately east of Wauswaugoning Bay. Notable exposures occur in Sections 24, 26, 27, 28, 33, and 34. The normal position of the red rock throughout is at the tops of large diabase sills. This is not the only occurrence, however, as may be observed at some of the exposures noted above. There are dike-like occurrences in SE¼ Section 33 and probably near the southeast corner of Section 34.

The series of exposures in the northeastern part of Section 27 seem to show conditions analogous to those on Pigeon Point; that is, a diabase is overlaid by or grades into an intermediate rock, which in turn is overlaid by red rock with quartzite inclusions, and this in turn by slate and quartzite. Contact metamorphism and crumpling of the slate is conspicuous adjacent to the major dikes.

Near the east quarter corner of Section 19 a vein appears in both banks of the river. On the Minnesota side about 12 inches of calcite with a few specks of hematite and possibly a little smithsonite make up the vein. In Section 24 a network of small veins of calcite occurs in the outcrops at Middle Falls. Along the gorge at the east quarter corner of Section 24 two calcite veins contain small amounts of pyrite, sphalerite, galena, and chalcopyrite.

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

A few paces northwest of the southwest corner of Section 29 a test pit shows pyrite and chalcopyrite in a sulphide diabase.

On the east section line of Section 28, about 750 paces south of the northeast corner, is a zone of sulphide diabase with much pyrrhotite.

Along a cliff about 200 paces east of the southwest corner of Section 29 is a zone of weathered sulphide diabase. This contains pyrite, pyrrhotite, chalcopyrite, and weathered products, limonite, and native copper. The zone appears to be about 2 feet wide and extends along the face of the bluff for 20 feet. Most of the zone was probably removed by erosion.

A prominent dike ridge ends rather abruptly to the east near the northeast corner of Section 31. At the east end of this ridge is a mineralized zone from 4 to 8 feet wide with diabase containing chalcopyrite and pyrrhotite on either side. A calcite-quartz vein which crosses the sulphide zone apparently is of later age and not connected with the sulphide mineralization, which appears to have been at least in part truly magmatic. Some analcite occurs in the wall of the carbonate vein.

In NW¼ Sec. 31 a small waterfall and gorge expose a calcite vein in sandstone and graywacke. The vein is about 3 feet wide. Quartz lines the walls and pyrite occurs along joints. The calcite is very coarse and forms a breccia with rock fragments, suggesting a possible fault.

Township 63 North, Range 6 East

Locations.—The area of this township except the east side of Hat Point was within the Grand Portage Indian Reservation and was resurveyed by the General Land Office in 1915, so locations as mapped are comparatively accurate. All section corners and many forty corners as well are marked by iron stakes.

Surface features.—This township comprises one of the most interesting historical areas in Minnesota, for the southeast end of the Grand Portage started from Grand Portage Bay on Lake Superior. This deep bay, protected by Hat Point and Grand Portage Island, is one of the best harbors northeast of Duluth on the Minnesota coast and was the site of the earliest settlement in Minnesota.[16]

North of the bay is a comparatively flat area, but to the east is the ridge of Hat Point, which culminates in Mount Josephine, at an elevation of 1,305 feet above sea level, or 700 feet above Lake Superior. Farther north and west in Section 6 high ridges and hills rise to a maximum height of 1,635 feet above sea level, as determined by barometer. This is but two miles from Grand Portage Bay. All the relatively flat area around Grand Portage Bay was submerged by the glacial stages of Lake Superior, and red glacial-lake clay is the prevailing soil.

Geology.—The structure and areal distribution of the formations cannot be completely deciphered in this township because of the extensive low areas covered with drift and lake deposits.

[16] Solon J. Buck, "The Story of the Grand Portage," *Minnesota History Bulletin,* 5:14–27 (1923).

The Keweenawan sandstones and basalts are partly exposed in Sections 7 and 8, so the southern boundary of the outcrop of Rove formation is closely determined. In Section 8 a prominent diabase dike cuts from the slate area directly across an outcrop of the Keweenawan sandstone and may be observed continuing a considerable distance to the southeast in flows overlying the sandstone. This is additional proof of the Keweenawan age of the Logan intrusives of this region.

The area around Grand Portage Bay is characterized by numerous small dikes in the slate, and the larger intrusives, particularly the Mount Josephine–Hat Point diabase, are also dikes.

An unusually good exposure of the contact of a dike with slate was observed on the high ridge in SW¼ Sec. 6. The typical granular texture of the metamorphosed slate hornfels grades within 100 feet to little-altered slate. A shear zone in the diabase near the contact contains chalcopyrite and pyrrhotite. The fact that dikes tend to drag up the sediments during intrusion is clearly shown near the end of Hat Point.

The exposures on Grand Portage Island are Keweenawan conglomerate and sandstone overlaid by basalt flows. Slate is exposed on the west side of Hat Point opposite the island, so it is clear that the unconformity passes between the island and the mainland.

Many detailed observations on the geology of Grand Portage Bay, Hat Point, and Mount Josephine may be found in the annual reports of the Minnesota Geological and Natural History Survey. These are summarized in the Final Report.[17]

With the exception of the sulphides noted above and minor calcite veins, no indications of mineralization were observed. Unusually fine specimens of pectolite were collected from the diabase near water level on the east side of Hat Point.

Townships 62 and 63 North, Range 7 East

Locations.—The original section corner marks for these townships are practically all missing, a rather severe forest fire having swept much of the area years ago. In establishing locations for mapping, use was made of the characteristic coast line and the town plat, supplemented by the topographic map of the point given by Bayley.[18]

Surface features.—Geologically, as well as from a scenic point of view, there is no region in Minnesota more interesting than Pigeon Point and the group of islands to the south. (See Figure 44.) The point proper projects into Lake Superior four miles beyond the mouth of the Pigeon River, and although very narrow, rises nearly 300 feet above the lake in places. The north side of the point is characteristically a bluff or cliff (see Figures 26 and 27), whereas the south shore dips gently under the lake. (See Figure 28.) This topography is a natural result

[17] N. H. Winchell and others, *Final Report of the Minnesota Geological and Natural History Survey*, 4:502–521.

[18] Bayley, *op. cit.*

of the sill of igneous rock which forms most of the point. Because of abundant moisture the rocks are covered in many places by a thick growth of moss.

The last mile and a half of the Pigeon River is a broad meandering stream with many sandbars and islands, in decided contrast to the turbulent stream above. This stretch of placid water begins about the middle of the north side of Section 30 below Pigeon River or High Falls. (See Figure 43.)

The rocky islands south of the point are probably a result of the resistance to erosion of the intrusives and flows which compose them.

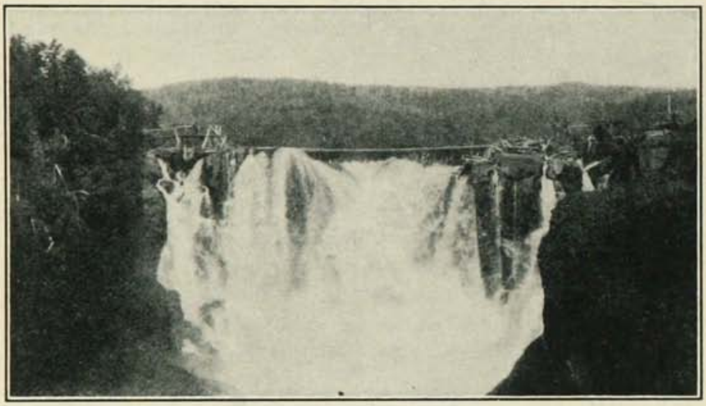


FIGURE 43. — Crest of Pigeon River Falls. A dike of diabase in slate caused the falls.

Several islands south of Pigeon Point are named differently on various maps. Compare, for example, the Pigeon Point plate of the fourth volume of the *Final Report of the Geological and Natural History Survey of Minnesota* and Plate III of United States Geological Survey Bulletin 109.

In this bulletin the names given by the United States Lake Survey charts have been used. The following list shows the alternative names.

U. S. Lake Survey	*Alternative*
Susie Island	Governor's Island
Lucille Island	High Island
Belle Rose Island	Magnet Island
Brick Island	Syenite Island
Little Brick Island	
Porcupine Island	

Geology. — The geology of Pigeon Point had been investigated by Bayley[19] and by Daly[20] previous to the detailed work in connection

[19] Bayley, *op. cit.*
[20] Daly, *op. cit.*

with the present study of the Rove slate area. Grout[21] has presented the results of this later work, and the whole subject is reviewed in the present report. (See pages 44 to 58.) The group of islands south of the point, however, are worthy of additional comment. Of most importance is the fact that the northern islands have Huronian rocks, whereas Lucille and Belle Rose, the two southerly islands, have only Keweenawan rocks, so the contact must run between.

The principal Keweenawan rocks are a series of basalt flows; but on the north side of Lucille Island the basal sandstone is like that exposed near the base of the Keweenawan from the farthest west

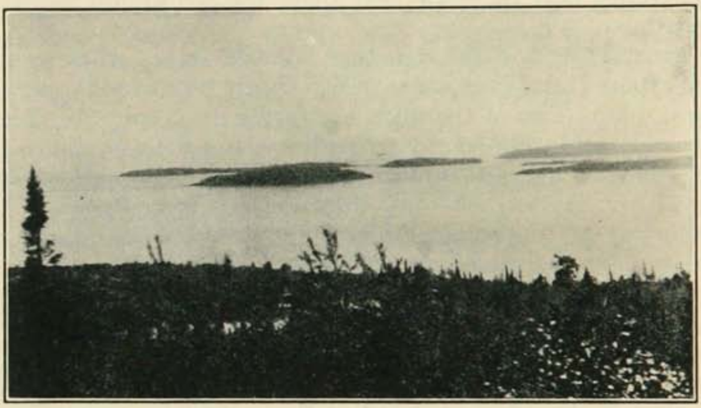


FIGURE 44. — Islands in Lake Superior south of Pigeon Point.

outcrop in T. 64 N., R. 3 E., to this final exposure in Minnesota territory. Brick Island and Little Brick Island also may be classified as Keweenawan, since they are composed entirely of intrusive rocks of Keweenanwan age. The relations to the slates on Susie Island, however, suggest that these rocks are intrusive into the Rove slates and quartzites. The two islands were named because of their brick-red color. Little Brick Island is entirely red rock (granite), but Brick Island shows a gradation from diabase through intermediate rock to red rock. These rocks are therefore counterparts of those exposed on Pigeon Point.

The other islands, of which Susie Island is by far the largest and most important, consist of a series of slates and graywackes intruded by diabase mainly in the form of dikes. The small island in the bay southeast of Susie Island is composed of slate intruded by a porphyritic diabase dike. On the dip slope of the slate is a small amount of sandstone or quartzite that may be a remnant of the basal Keweenawan sandstone. If this is the case the unconformity is located exactly.

On Susie Island the sediments strike N. 70° E. to N. 80° E. and dip 18° S. The dikes are at right angles to the bedding and most of them

[21] F. F. Grout, *op. cit.*

also strike about N. 75° E. They range from 20 to 50 feet wide, and each shows variation. An especially resistant dike accounts for the northern peninsula of the island, which joins the main part of the island only through a low swampy area without outcrops. A series of four or more dikes make the high ridges in the north-central part of the island, and it is here that some veins have been prospected. Again there is a swampy area between this and a group of dike outcrops on the south side of the island. This low area has on the eastern side a beach gravel deposit of granite such as outcrops on Little Brick Island near by; and there may be a sill of such material concealed by surface deposits on Susie Island. Winchell states that the shaft near shore reached granite before it was abandoned.

The general trend of the structure is easily traced where some dikes are well exposed, and even more positively by petrographic peculiarities of certain dikes. Two of the dikes are distinctly porphyritic in contrast with the rest, and were traced across the island with no difficulty.

The sediments are not so much affected by contact action near these comparatively narrow dikes as they are by some larger dikes and sills occurring on the mainland near by. Nevertheless there is some brecciation, especially where two nearly parallel dikes were intruded within a few feet of each other. Such pairs of dikes seem to be a very characteristic structural feature of the whole district. The breccia at the incline on Susie Island is cemented with calcite and other gangue minerals, but has too little copper to be considered ore. The ore of the calcite veins is described in detail in the section on economic geology.

The geology at the Pigeon River Falls at the north side of Section 30 has been described by Winchell[22] and by Bayley.[23] The slates are intruded by a dike which strikes N. 50° E. and forms the falls and a ridge on each side of the river. Below the falls is a second dike, and there is some evidence of a sill. The structure below the falls is probably not so simple as that sketched by Winchell, but the difference is not important. Bayley described the falls as follows:

> At the falls of the Pigeon River the joint cracks have a direction S. 79° W. and N. 11° W., so that the loosening of large masses of the rocks from the barrier of the falls results in the formation of a perpendicular wall over which the river plunges vertically to a depth of about 120 feet, taking a second smaller plunge over a trap dike, which runs parallel to the larger dike at a distance of about 50 yards east of it.

Several veins on Pigeon Point deserve brief mention. On the shore of Pigeon Bay at the center line of Section 28 is a calcite-barite vein in a cliff at the water's edge. This is about 30 inches wide and cuts slate near a dike. The abundance of barite is noteworthy. To the east a short distance is a series of dip joints and shear zones in slate, along which calcite veins have formed. Winchell[24] reported some work on a vein three-fourths of a mile east of the point that encloses Clark's

[22] *Op. cit.*, p. 508.
[23] Bayley, *op. cit.*
[24] *Op. cit.*

(Mark's) Bay. The minerals were calcite, barite, amethyst, pyrite, sphalerite, galena, and chalcopyrite.

In Section 27 on the south shore of the point in a small bay in the western part of the section is a similar calcite-barite vein in slate that is about 8 feet wide near the shore, where it is well exposed. This is the widest of the calcite veins observed. The main vein strikes northwest-southeast, and a branch about 2 feet wide extends to the southwest.

In Section 32 small calcite veins are visible along shore and under water, but these do not contain any metallic minerals.

Just west of Morrison's Bay is a series of pits in a graphitic, pyritic quartzite 20 feet wide. About 100 paces west of the pits is a calcite vein with more or less barite and quartz. The pit farthest north exposes the vein to a width of 6 feet, mainly calcite, with a vug on the hanging wall containing amethystine quartz. Winchell[25] reported galena and malachite from a vein that corresponds with this one in location. A short tunnel also cuts the vein. The strike is about N. 15° W., dip 60° S. The vein shows a breccia in some places and also banding, which suggests successive opening and filling.

On the shore at about the center line of Section 31 is another series of calcite veins along joint planes in quartzite. These are mainly under water and follow strike joints, occasionally cutting across from one strike joint to another along dip joints. The main vein is about a foot thick.

[25] Winchell, Seventh Annual Report of the Minnesota Geological and Natural History Survey, p. 15.

INDEX

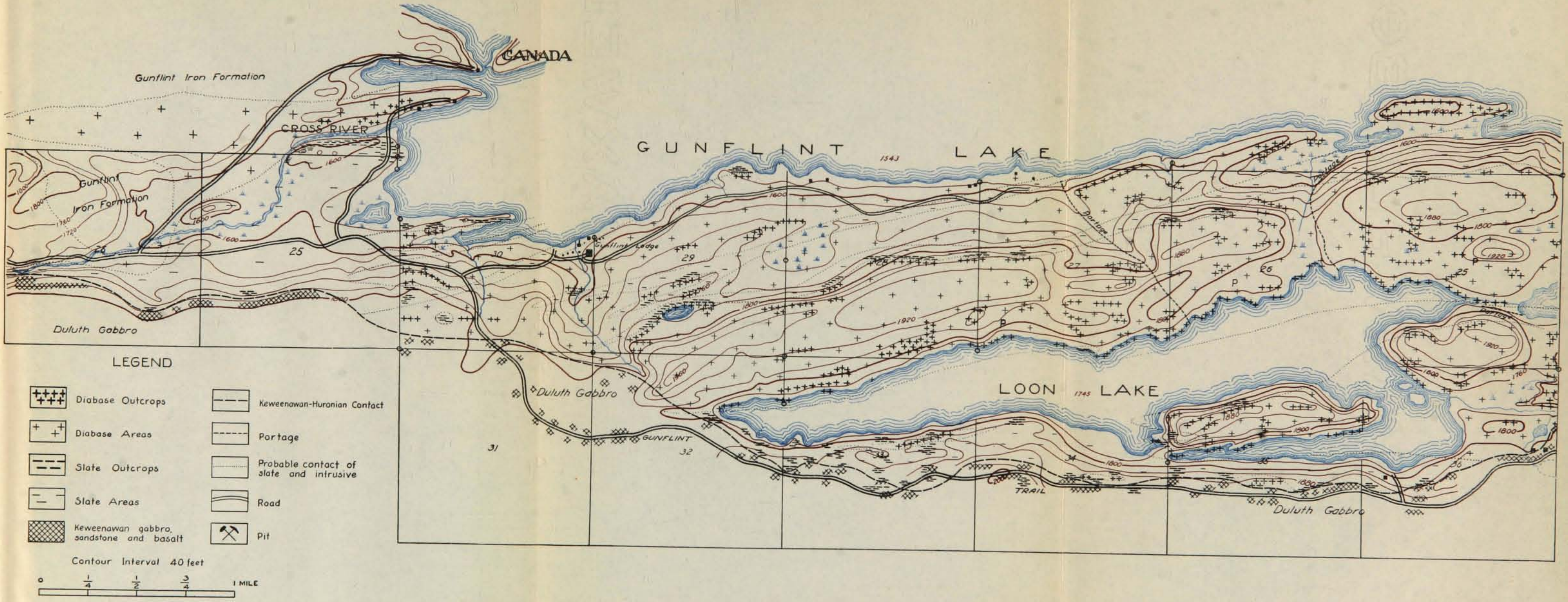


PLATE I—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 65 NORTH, RANGES 3 AND 4 WEST

PLATE 2—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 65 NORTH, RANGE 2 WEST

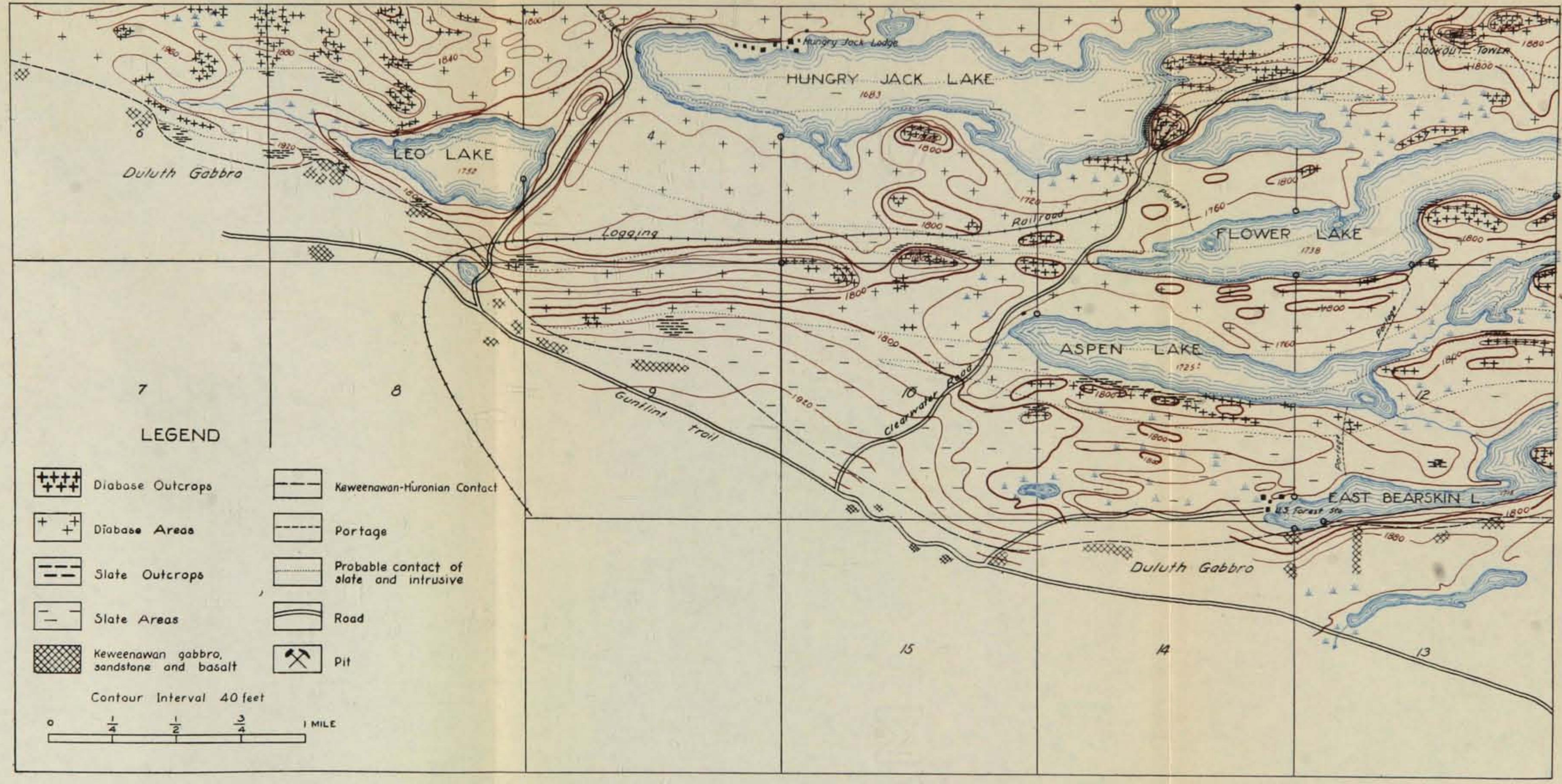


PLATE 3—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 64 NORTH, RANGE 1 WEST

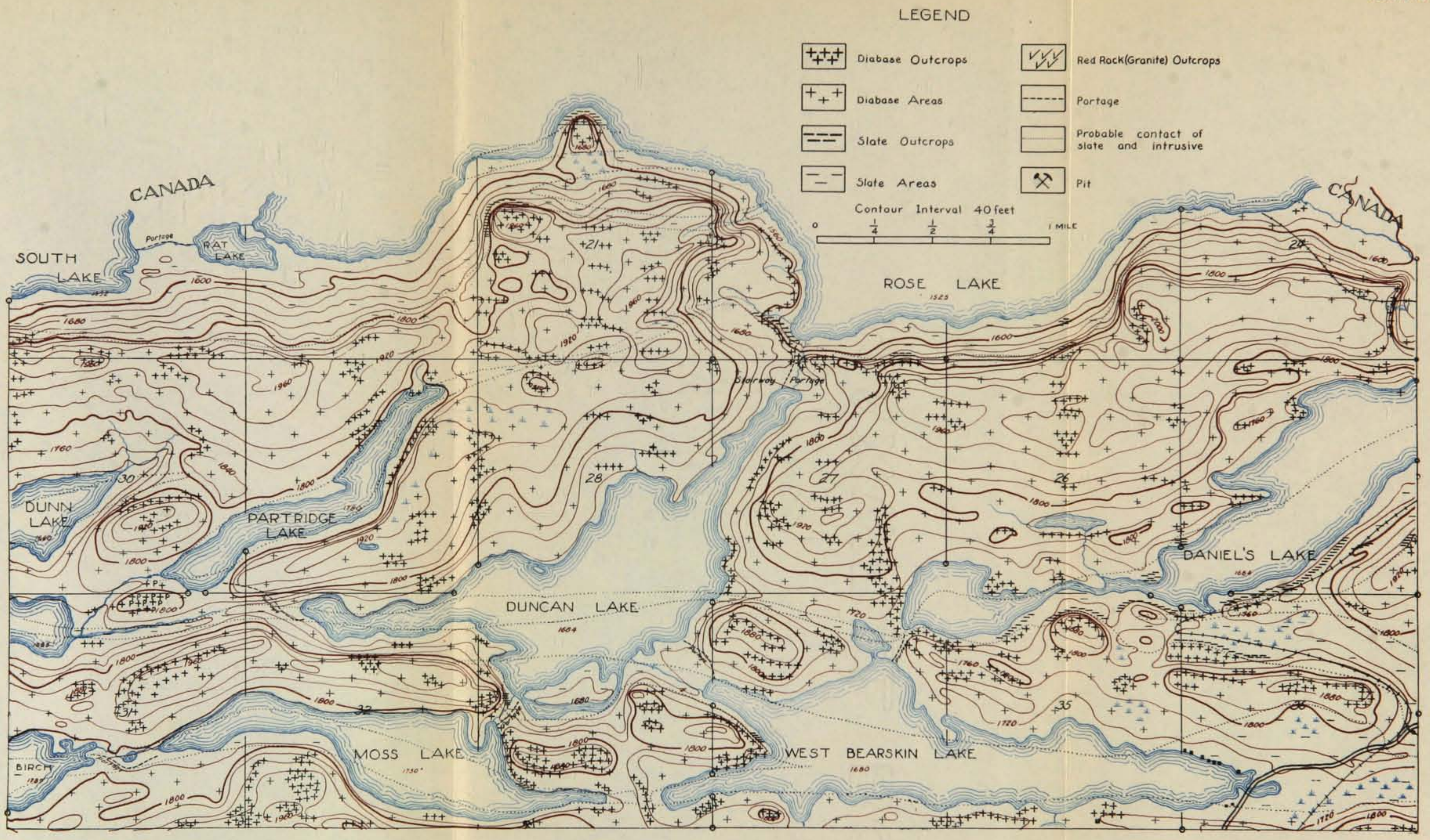


PLATE 4—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 65 NORTH, RANGE 1 WEST

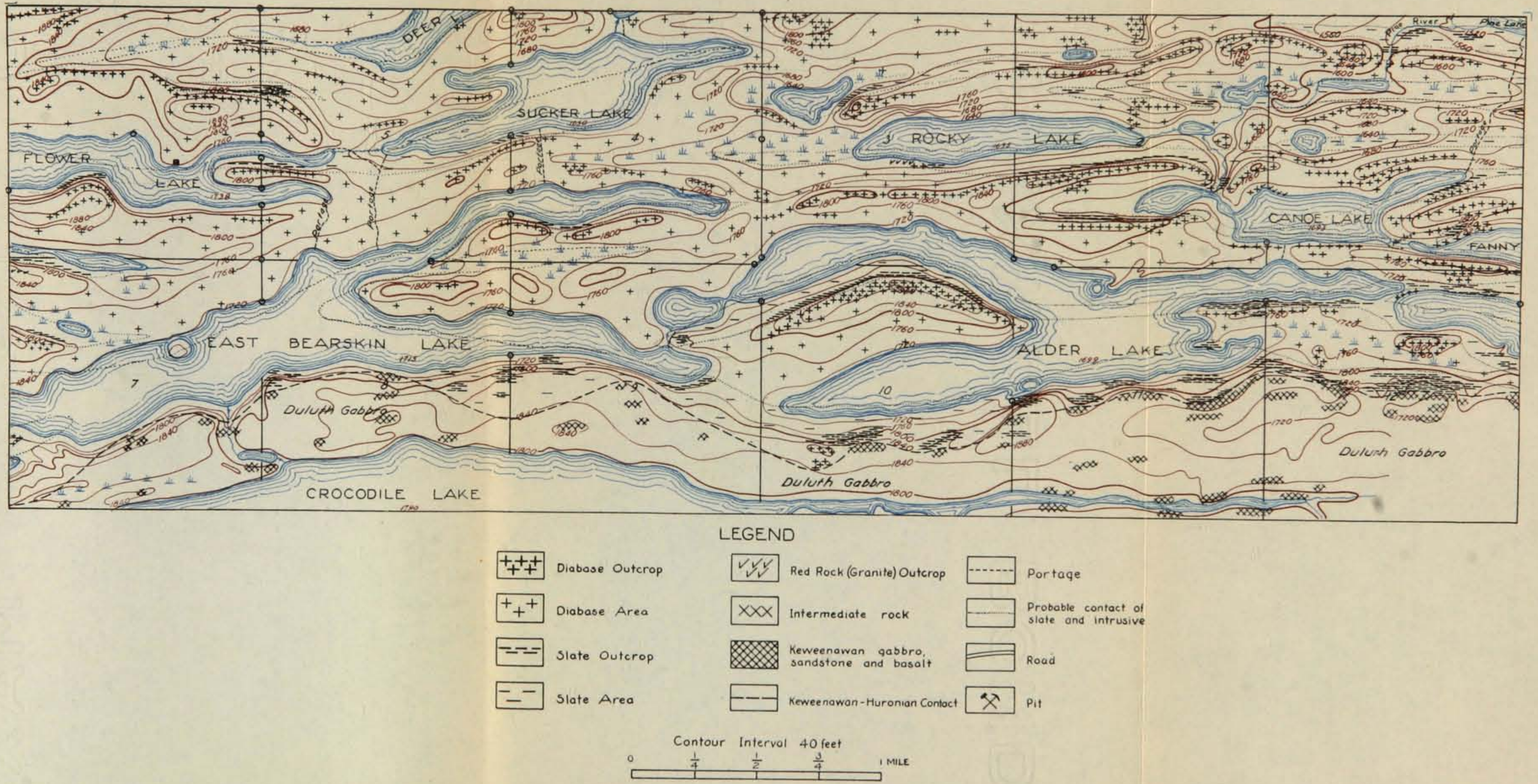


PLATE 5—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 64 NORTH, RANGE 1 EAST

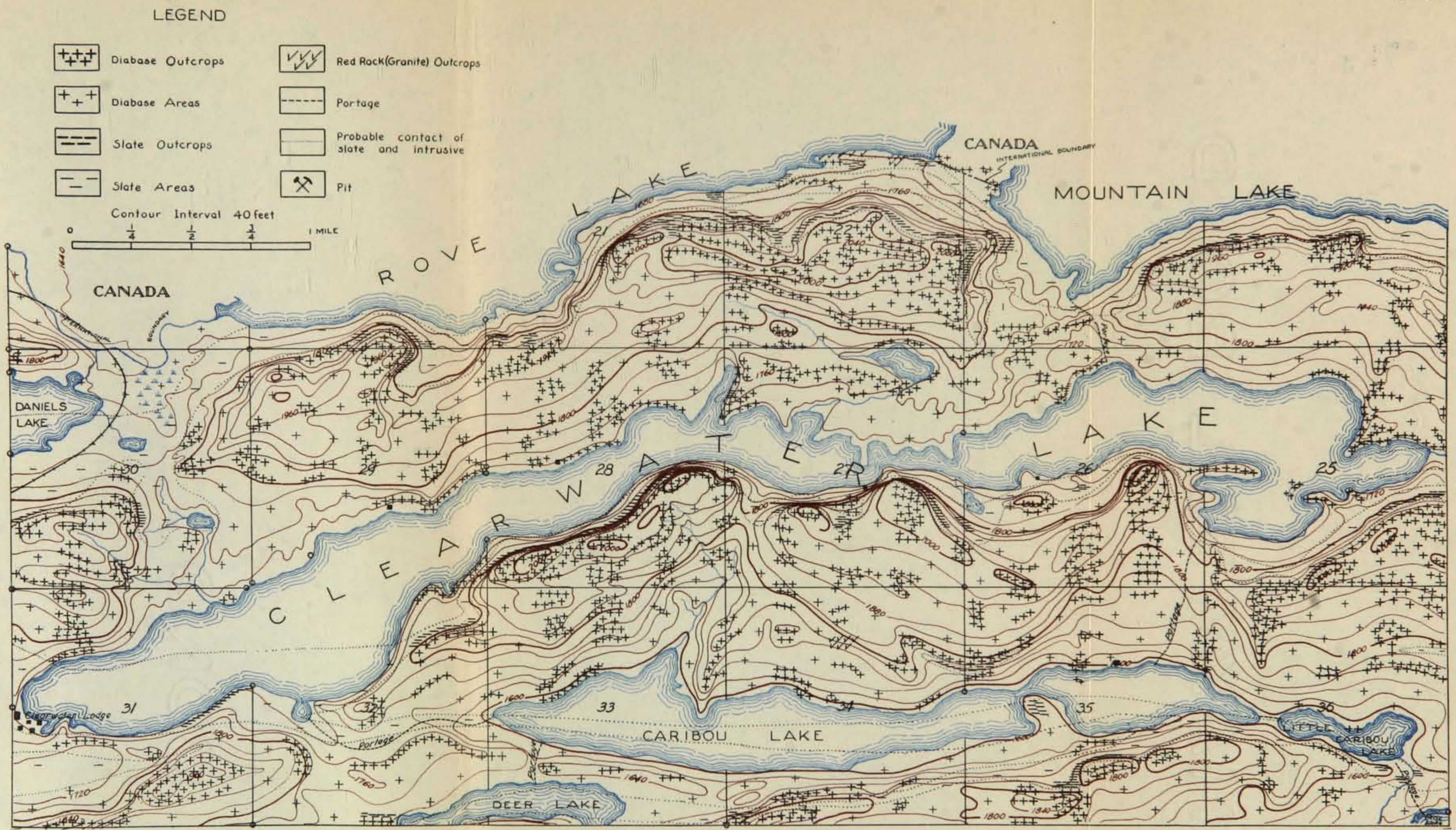


PLATE 6—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 65 NORTH, RANGE 1 EAST

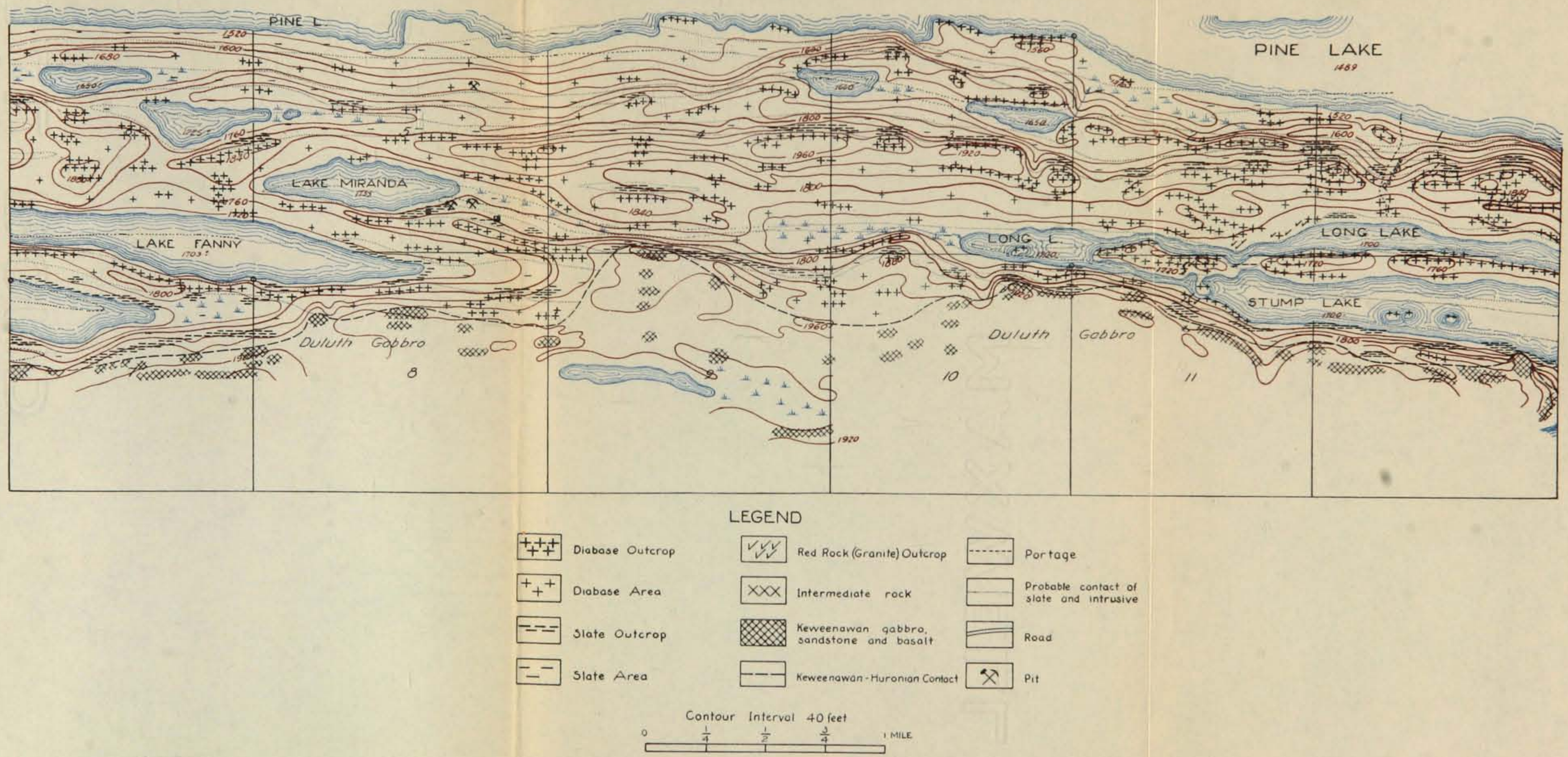


PLATE 7—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 64 NORTH, RANGE 2 EAST

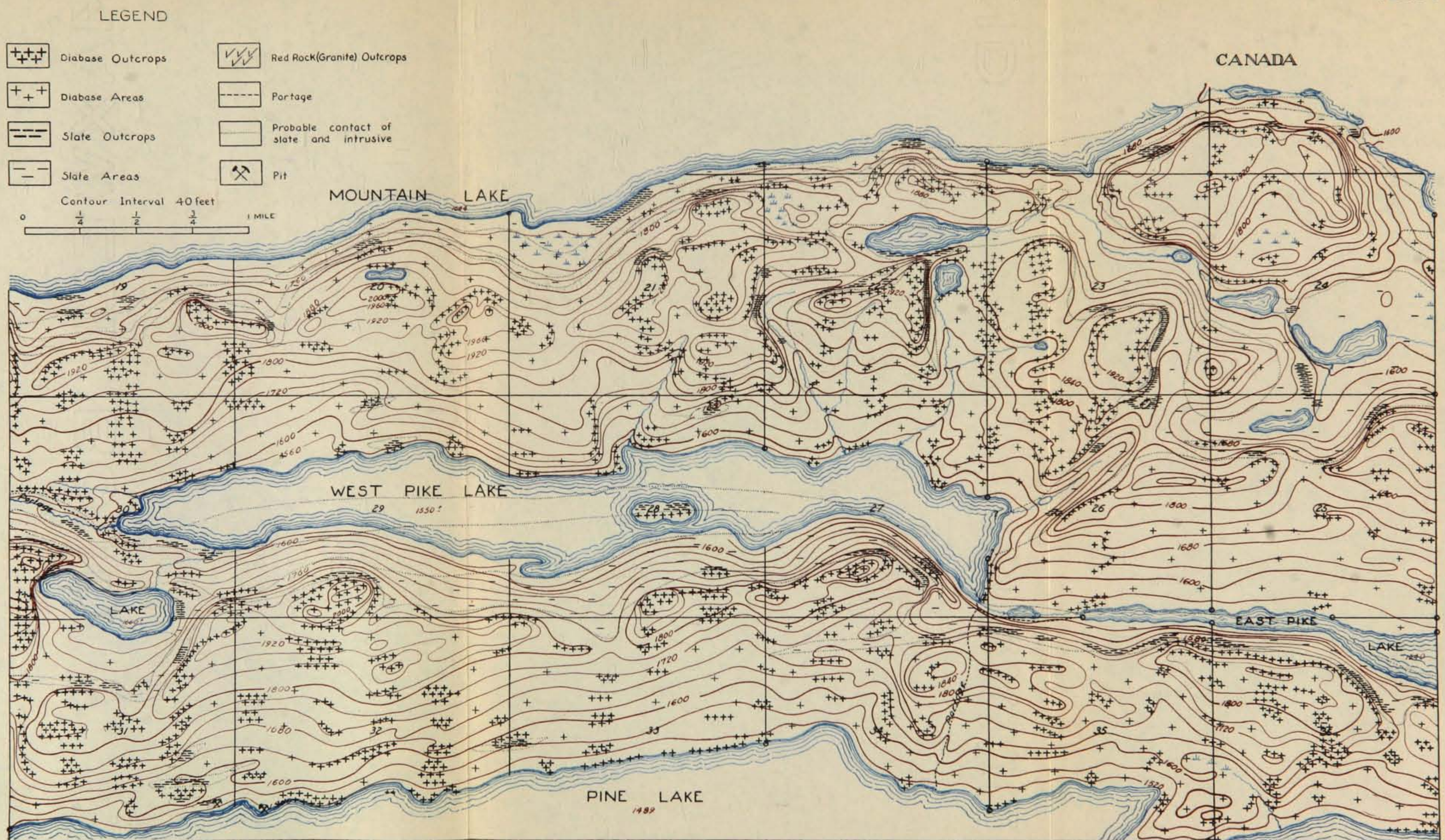


PLATE 8—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 65 NORTH, RANGE 2 EAST

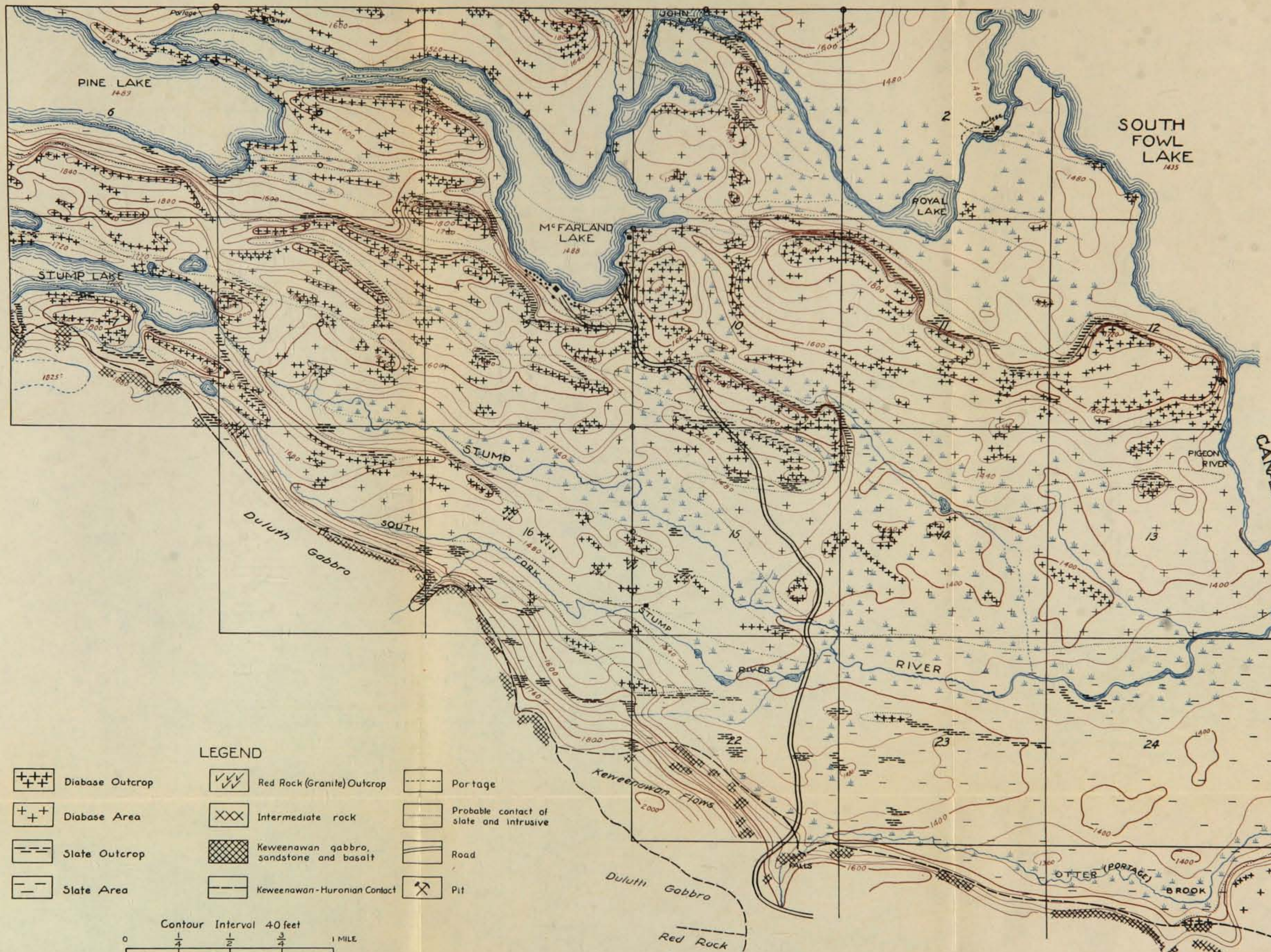


PLATE 9—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 64 NORTH, RANGE 3 EAST

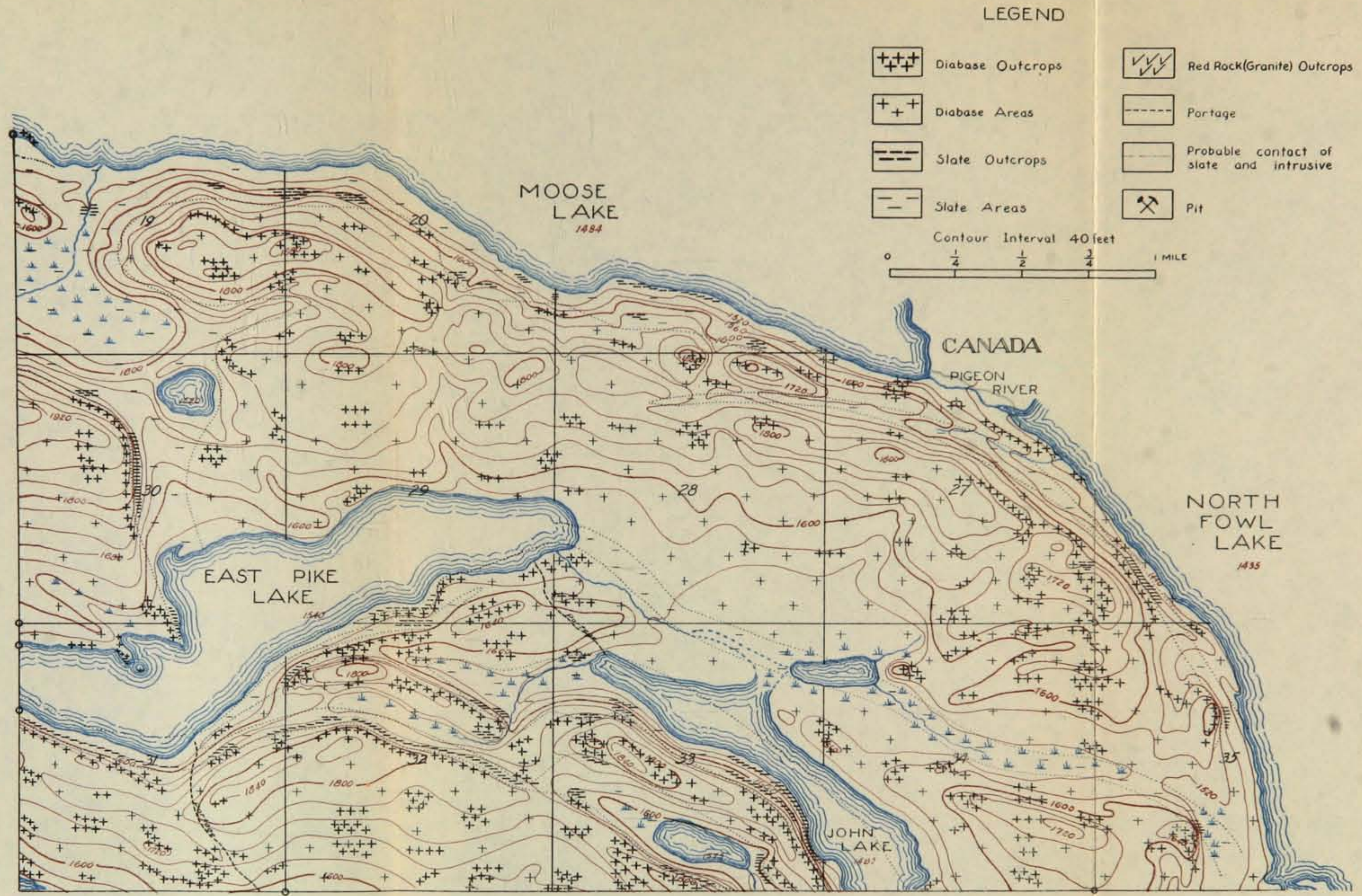


PLATE 10—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 65 NORTH, RANGE 3 EAST

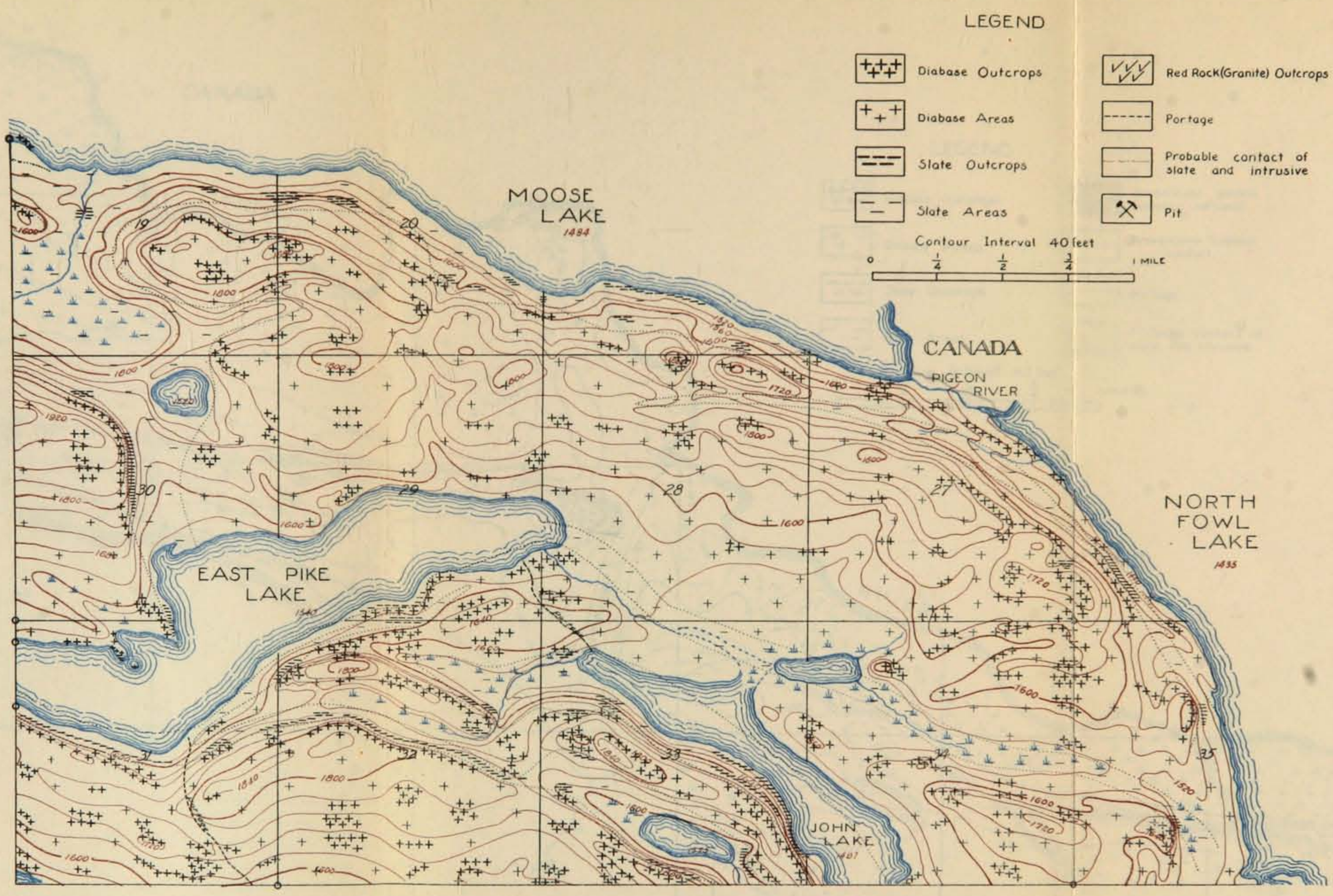


PLATE 10—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 65 NORTH, RANGE 3 EAST

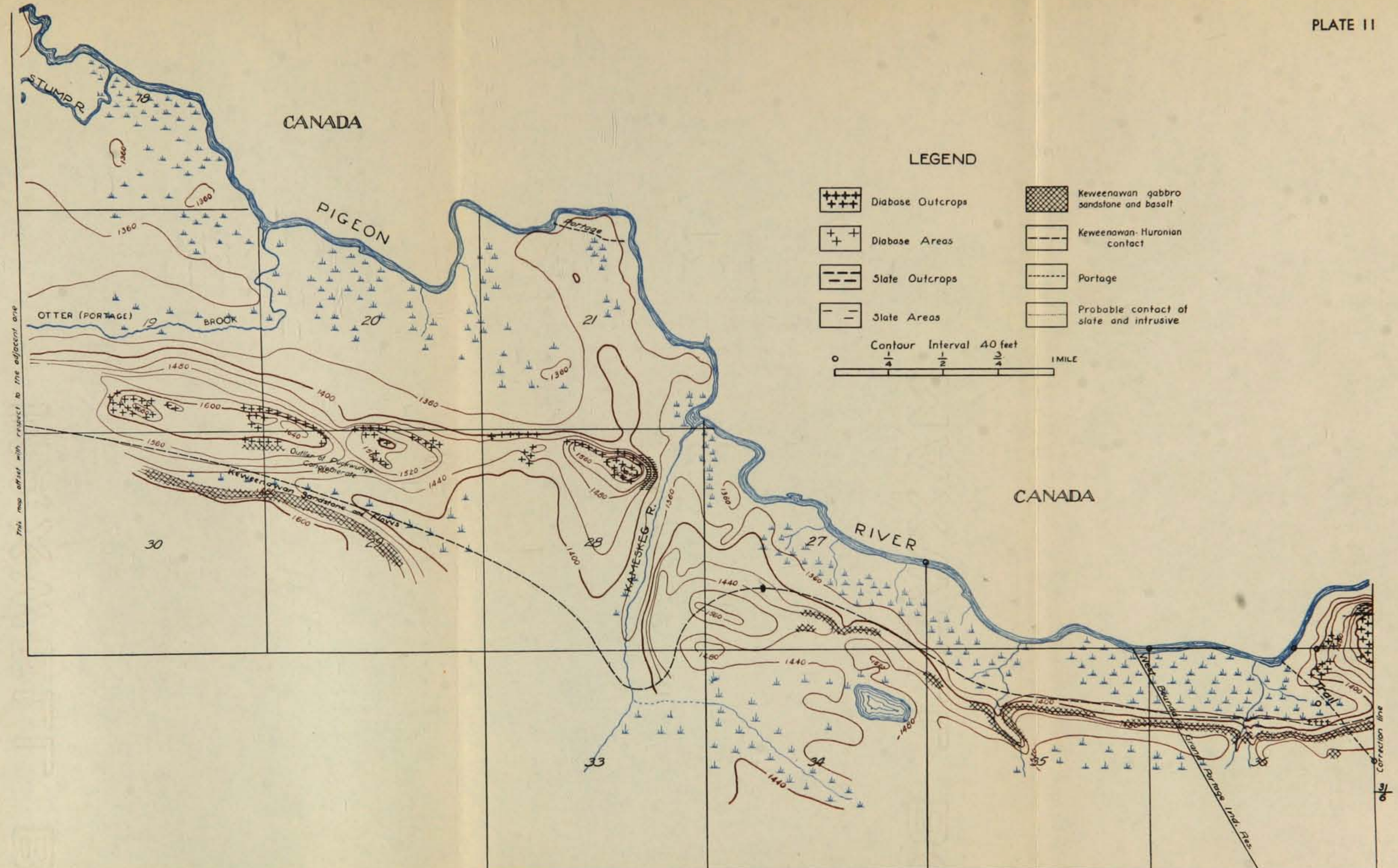
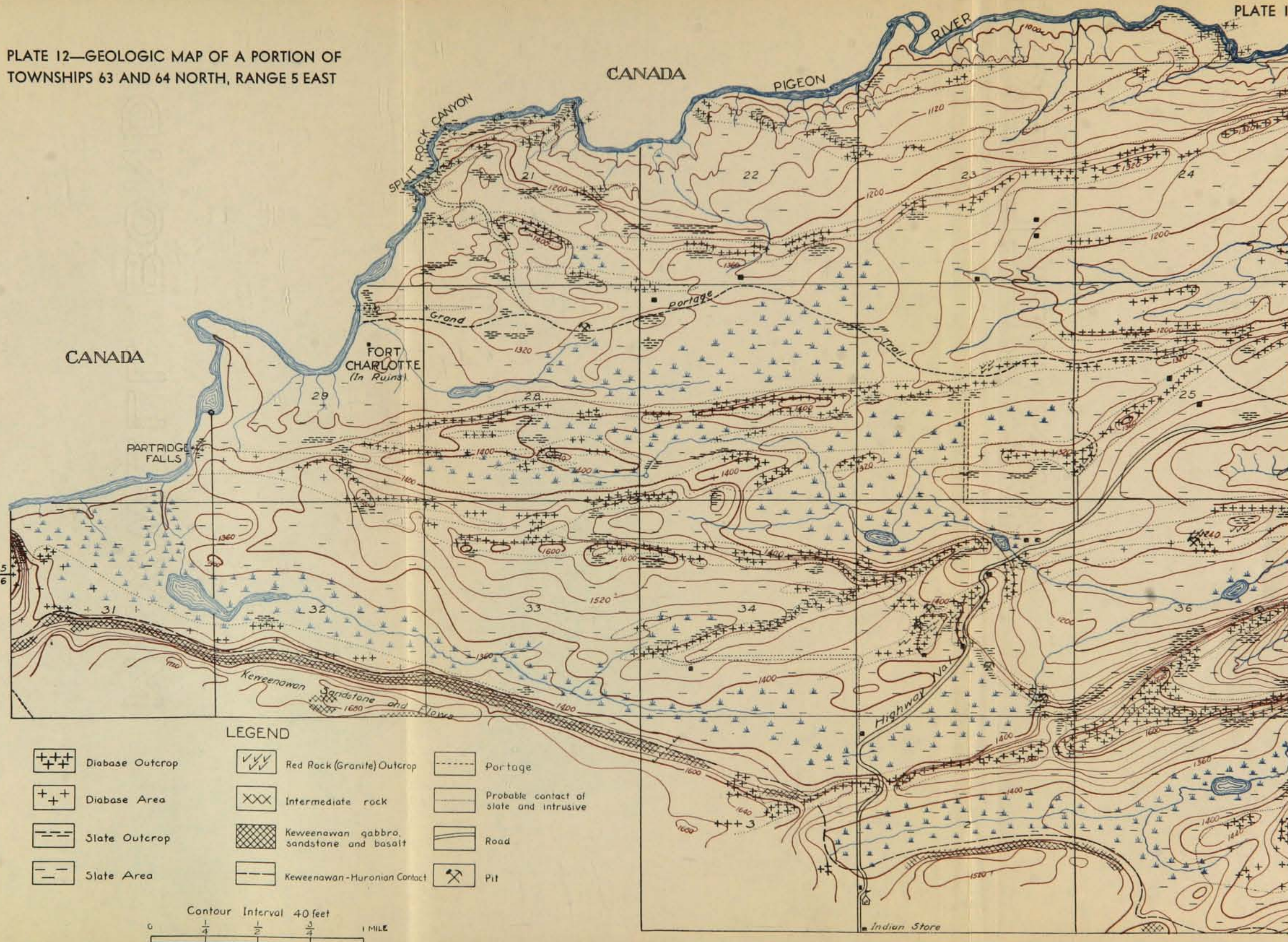


PLATE 11—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 64 NORTH, RANGE 4 EAST

PLATE 12—GEOLOGIC MAP OF A PORTION OF TOWNSHIPS 63 AND 64 NORTH, RANGE 5 EAST



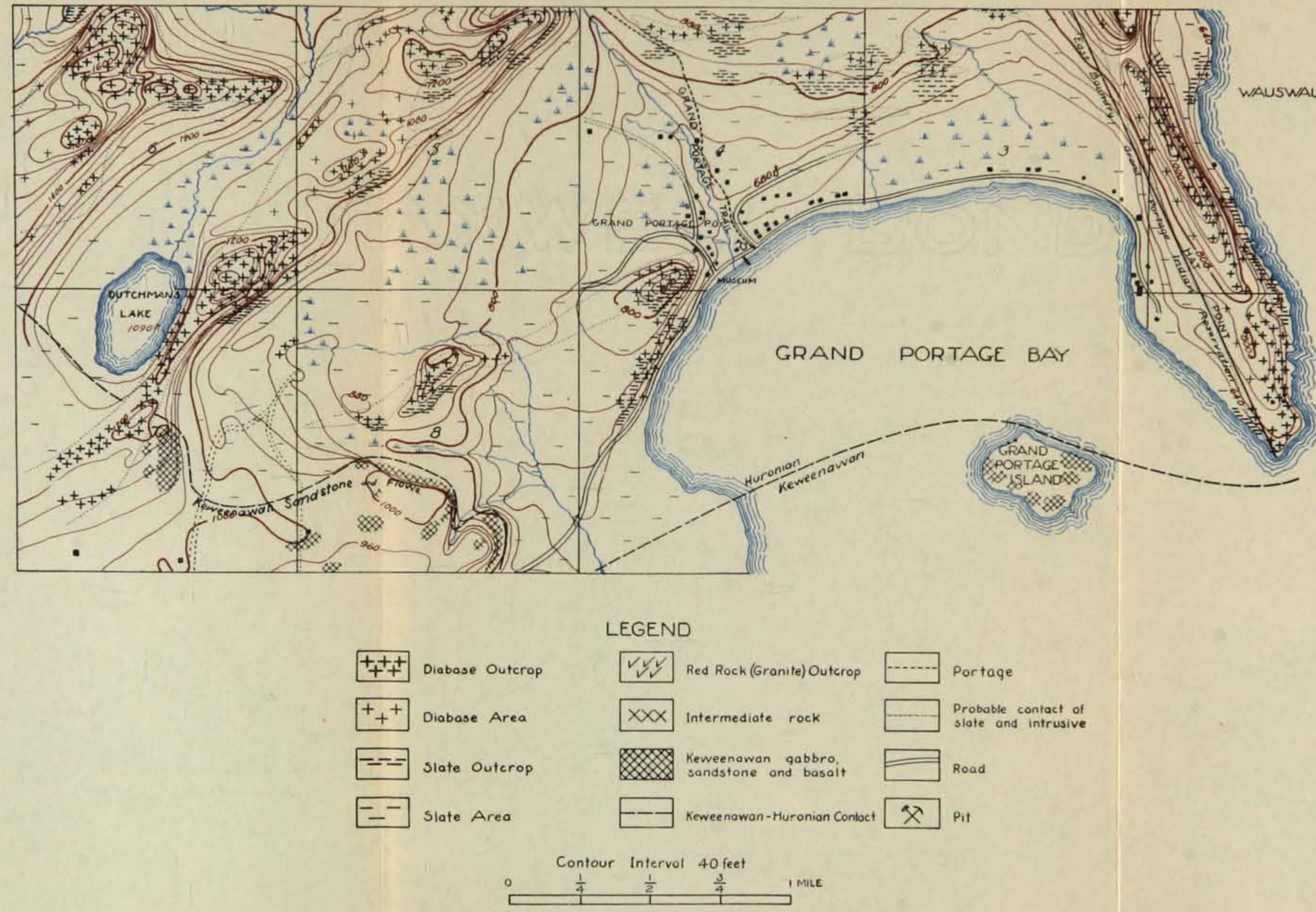


PLATE 13--GEOLOGIC MAP OF A PORTION OF TOWNSHIP 63 NORTH, RANGE 6 EAST

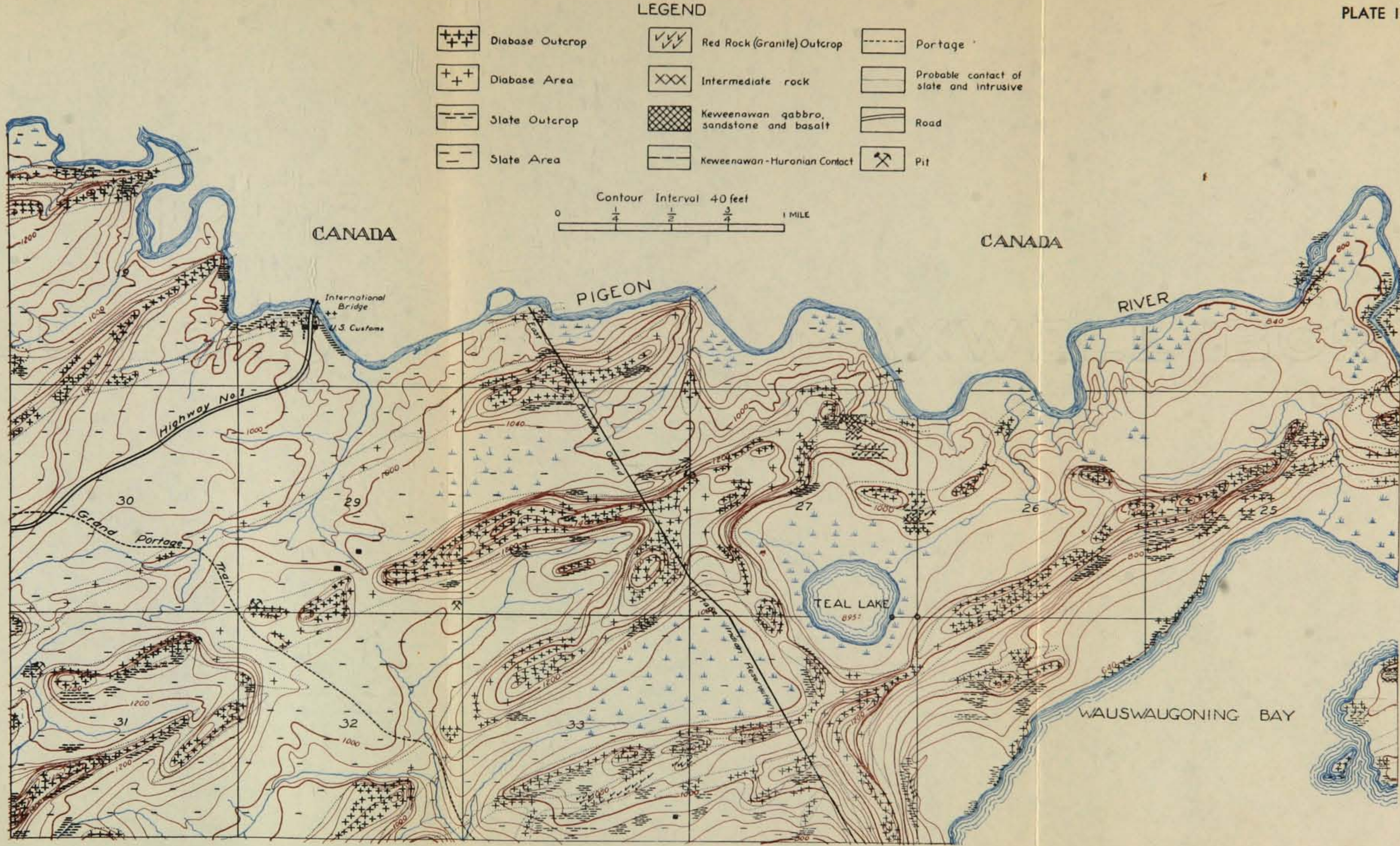


PLATE 14—GEOLOGIC MAP OF A PORTION OF TOWNSHIP 64 NORTH, RANGE 6 EAST

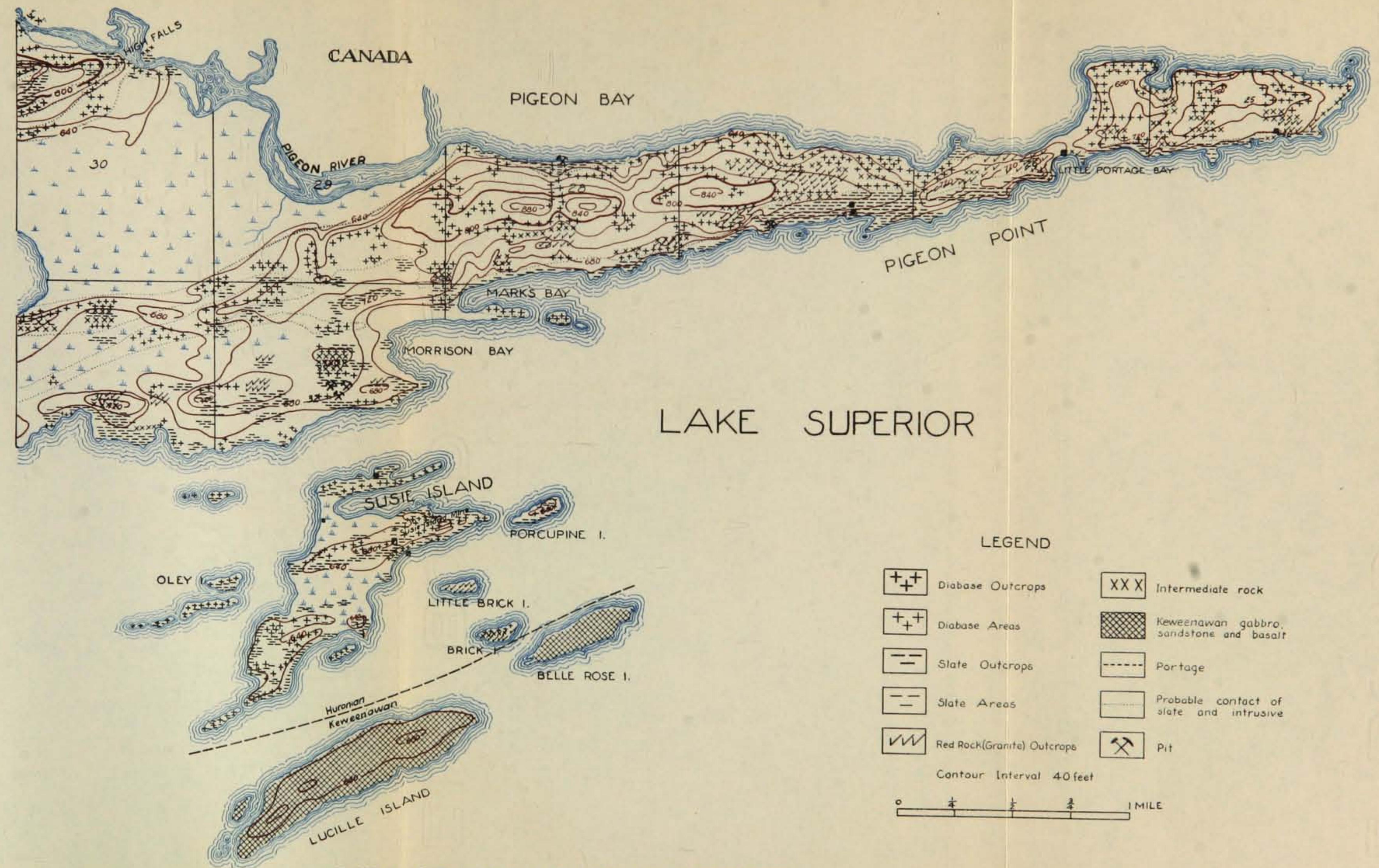
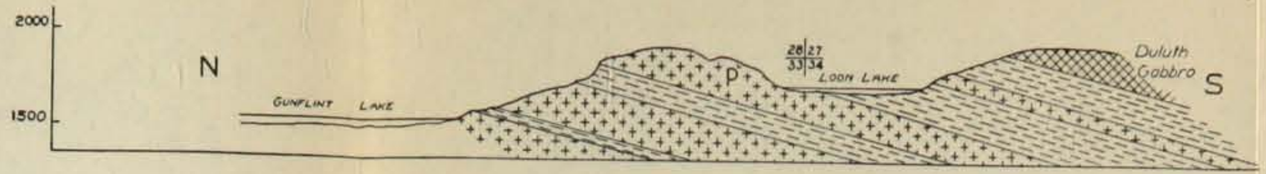
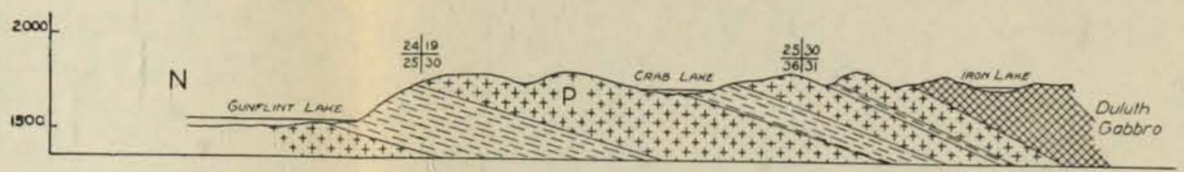


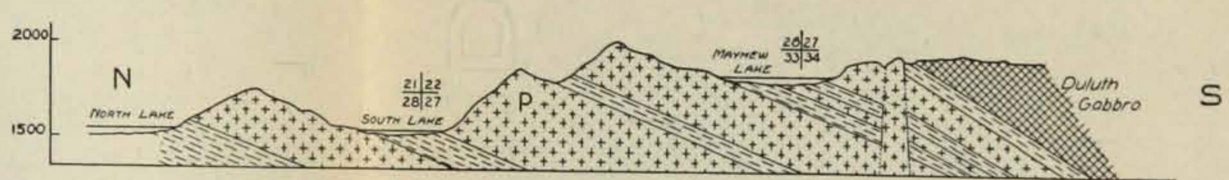
PLATE 15—GEOLOGIC MAP OF A PORTION OF TOWNSHIPS 63 AND 64 NORTH, RANGE 7 EAST



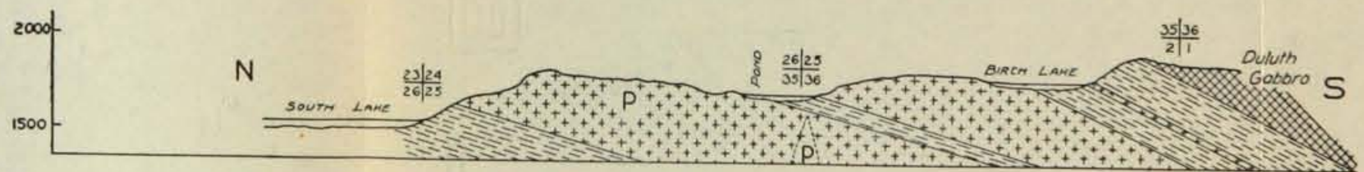
CROSS SECTION THREE MILES WEST OF EAST RANGE LINE, TOWNSHIP 65 NORTH, RANGE 3 WEST



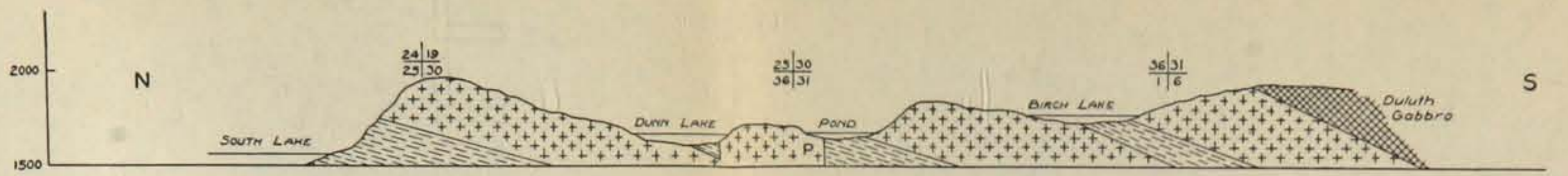
CROSS SECTION ON RANGE LINE BETWEEN RANGES 2 AND 3 WEST, TO WNSHIP 65 NORTH



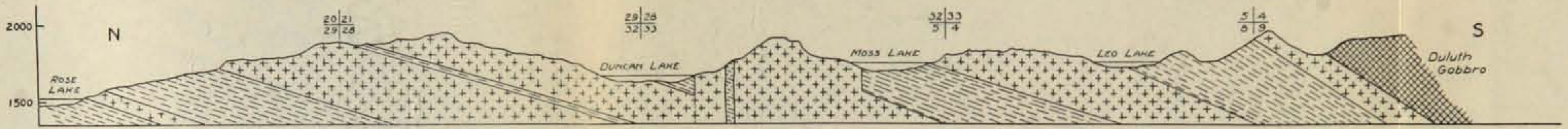
CROSS SECTION THREE MILES WEST OF EAST RANGE LINE, TOWNSHIP 65 NORTH, RANGE 2 WEST



CROSS SECTION ONE MILE WEST OF EAST RANGE LINE, TOWNSHIP 65 NORTH, RANGE 2 WEST

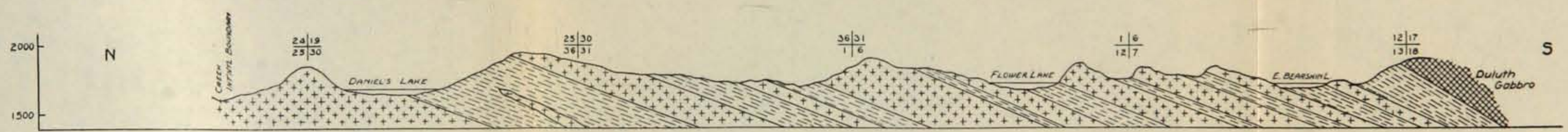


CROSS SECTION ON RANGE LINE BETWEEN RANGES 1 AND 2 WEST, TOWNSHIPS 64 AND 65 NORTH

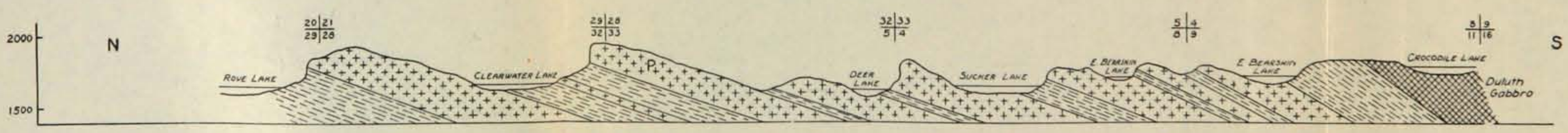


CROSS SECTION TWO MILES EAST OF RANGE LINE, TOWNSHIPS 64 AND 65 NORTH, RANGE 1 WEST

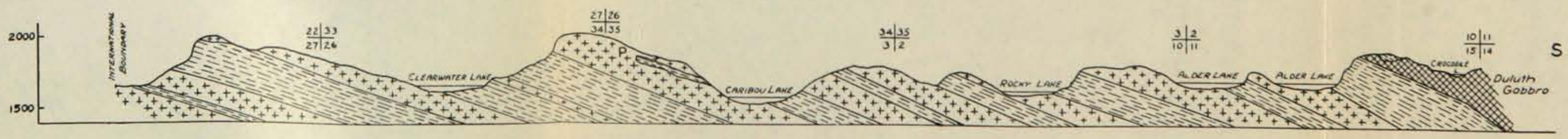
CROSS SECTION TWO MILES WEST OF EAST RANGE LINE, TOWNSHIPS 64 AND 65 NORTH, RANGE 1 WEST



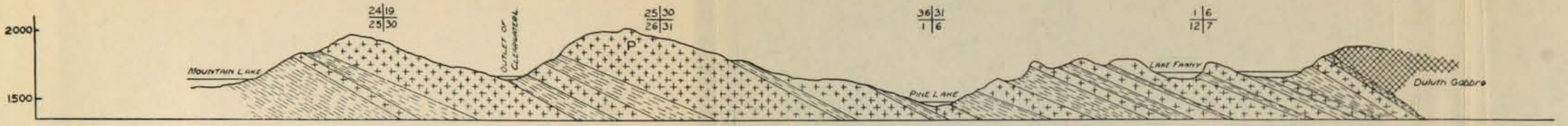
CROSS SECTION ON FOURTH PRINCIPAL MERIDIAN ON RANGE LINE BETWEEN RANGES 1 WEST AND 1 EAST, TOWNSHIPS 64 AND 65 NORTH



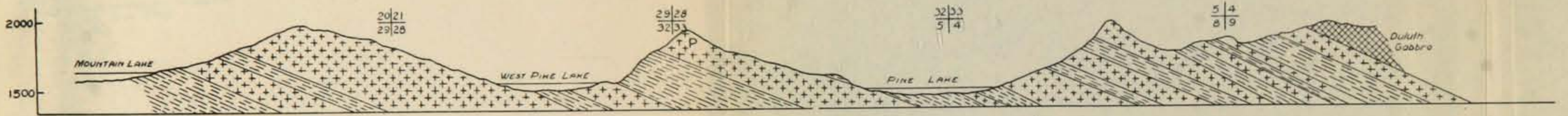
CROSS SECTION TWO MILES EAST OF FOURTH PRINCIPAL MERIDIAN, TOWNSHIPS 64 AND 65 NORTH, RANGE 1 EAST



CROSS SECTION FOUR MILES EAST OF FOURTH PRINCIPAL MERIDIAN, TOWNSHIPS 64 AND 65 NORTH, RANGE 1 EAST

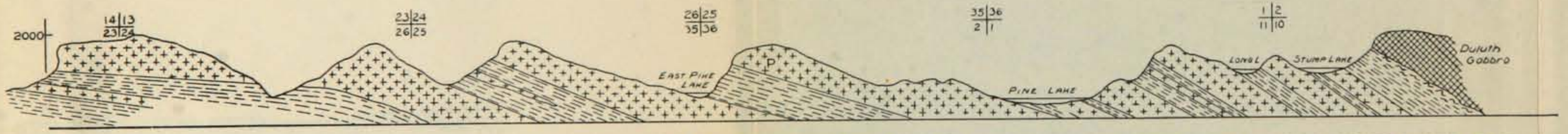


CROSS SECTION ON RANGE LINE BETWEEN TOWNSHIPS 64 AND 65 NORTH, RANGES 1 AND 2 EAST

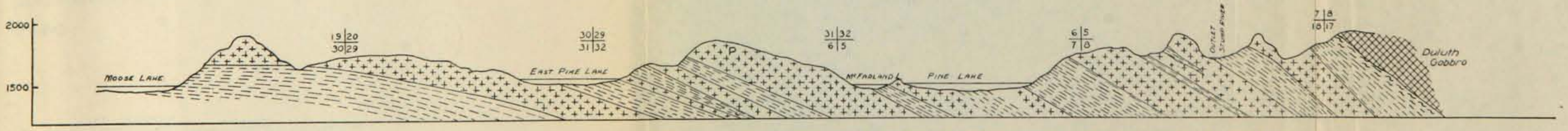


CROSS SECTION TWO MILES EAST OF WEST RANGE LINE OF TOWNSHIPS 64 AND 65 NORTH, RANGE 2 EAST

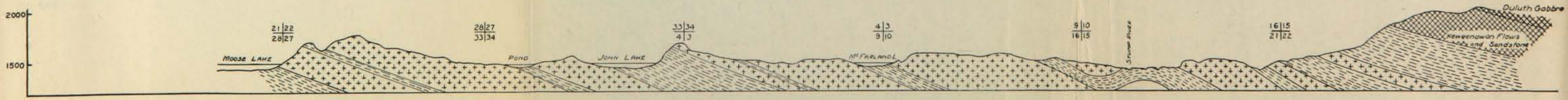
CROSS SECTION TWO MILES WEST OF EAST RANGE LINE OF TOWNSHIPS 64 AND 65 NORTH, RANGE 2 EAST



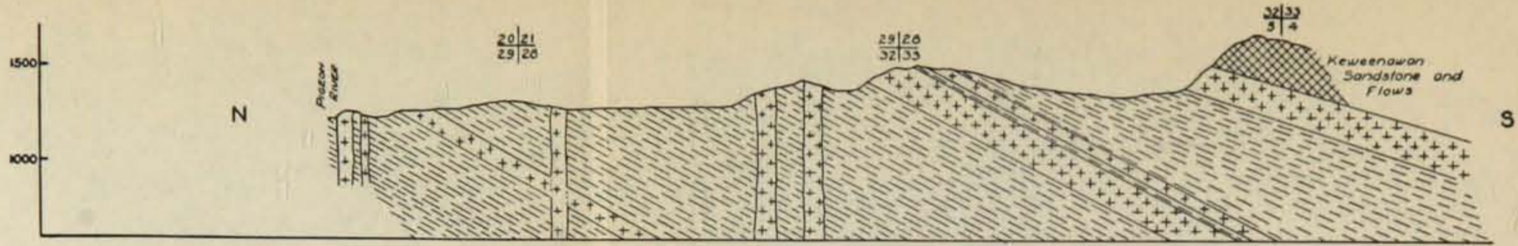
CROSS SECTION ONE MILE WEST OF EAST RANGE LINE OF TOWNSHIPS 64 AND 65 NORTH, RANGE 2 EAST



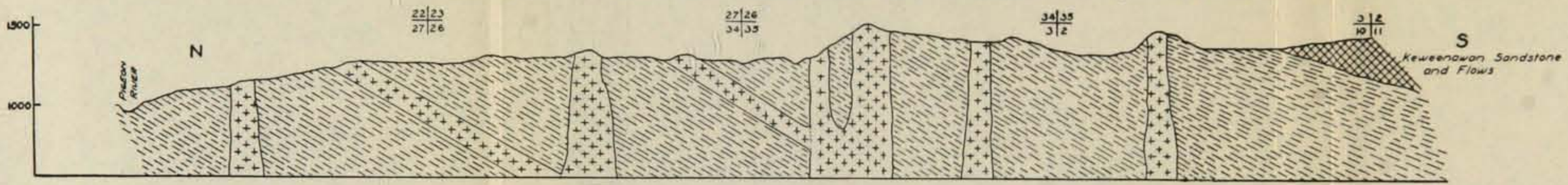
CROSS SECTION ONE MILE EAST OF WEST RANGE LINE OF TOWNSHIPS 64 AND 65 NORTH, RANGE 3 EAST



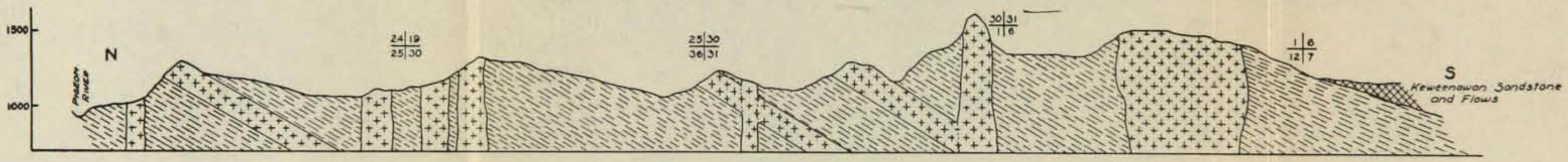
CROSS SECTION THREE MILES EAST OF WEST RANGE LINE OF TOWNSHIPS 64 AND 65 NORTH, RANGE 3 EAST



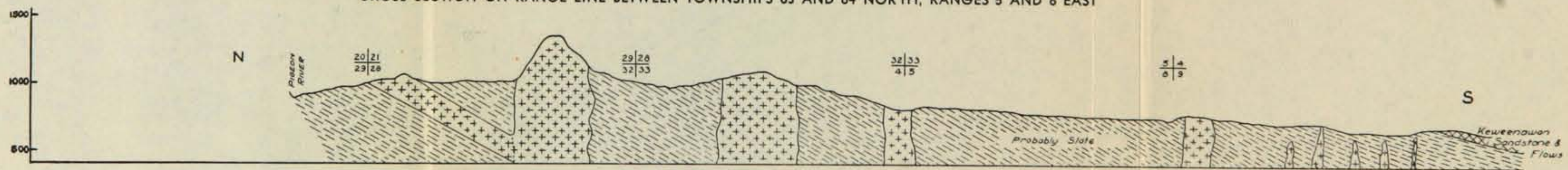
CROSS SECTION TWO MILES EAST OF WEST RANGE LINE, TOWNSHIP 64 NORTH, RANGE 5 EAST



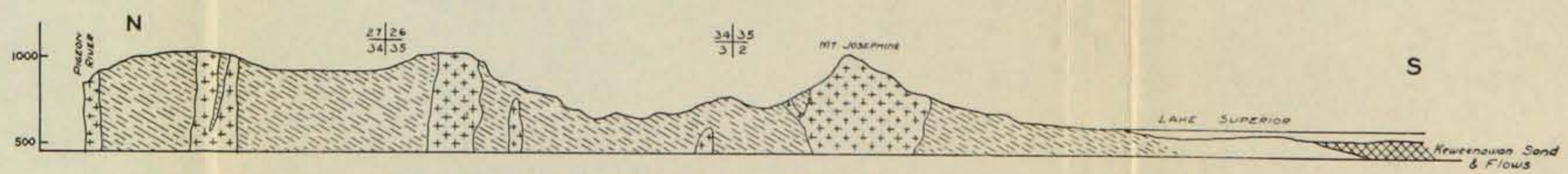
CROSS SECTION TWO MILES WEST OF EAST RANGE LINE, TOWNSHIPS 63 AND 64 NORTH, RANGE 5 EAST



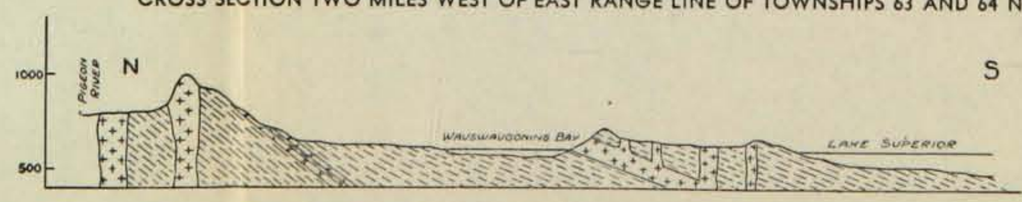
CROSS SECTION ON RANGE LINE BETWEEN TOWNSHIPS 63 AND 64 NORTH, RANGES 5 AND 6 EAST



CROSS SECTION TWO MILES EAST OF WEST RANGE LINE OF TOWNSHIPS 63 AND 64 NORTH, RANGE 6 EAST



CROSS SECTION TWO MILES WEST OF EAST RANGE LINE OF TOWNSHIPS 63 AND 64 NORTH, RANGE 6 EAST



CROSS SECTION ON EAST RANGE LINE, TOWNSHIP 64 NORTH, RANGE 6 EAST


UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
W. H. EMMONS, DIRECTOR
GEOLOGIC MAP
OF THE
ROVE SLATE AREA
MINNESOTA
BY FRANK F. GROUT AND G. M. SCHWARTZ
1930
0 1 2 3 4 5 6 MILES
KEWEENAWAN
Diabase intrusives (Logan sills etc.) in Rove Formation
Duluth Gabbro, Puckwunge conglomerate, Sandstone, Flows, Diabase intrusives
HURONIAN
Rove Formation
CANADA
CANADA
CANADA
NORTH LAKE
SOUTH LAKE
GUNFLINT LAKE
LOON LAKE
MOUNTAIN LAKE
WEST PIKE LAKE
PINE LAKE
NORTH FOWL LAKE
SOUTH FOWL LAKE
PIGEON RIVER
PIGEON BAY
PIGEON POINT
LAKE SUPERIOR
R4W
R3W
R2W
R1W
R1E
R2E
R3E
R4E
R5E
R6E
T63N
T64N
T65N