MINNESOTA GEOLOGICAL SURVEY

MATT WALTON, *Director*

GEOLOGY OF THE MILEPOST 7 AREA, LAKE COUNTY, MINNESOTA

John C. Green

Report of Investigations 26

ISSN 0076-9177

UNIVERSITY OF MINNESOTA

Saint Paul - 1982

GEOLOGY OF THE
MILEPOST 7 AREA,
LAKE COUNTY, MINNESOTA

CONTENTS

ILLUSTRATIONS

TABLES

GEOLOGY OF THE MILEPOST 7 AREA, LAKE COUNTY, MINNESOTA

by

John C. Green

INTRODUCTION

Field work in the Milepost 7 area was done primarily in the summer of 1978 with other visits in October 1976 and in August 1979 during the construction of a taconite-tailings disposal basin for Reserve Mining Company's mill in Silver Bay. Operation of the facility began in 1980 and during its 40-year projected use the basin is designed to be filled to an elevation of 1,309 feet.

Much technical information on the project and its environmental aspects can be obtained from various reports by the U.S. Army Corps of Engineers and the firms of Arthur D. Little, Inc., and Klohn Leonoff Consultants, Ltd., consultants to Reserve Mining Company. These are listed in the Reference section.

Earlier geologic studies include the regional reconnaissance report of Grout and Schwartz (1939), which covers the southeastern two-thirds of the Milepost 7 area, and the petrologic investigations of Gehman (1957) on the intrusive rocks that occur in the eastern third of the area. The report of the Minnesota Coastal Zone Management Program (Green and others, 1977) includes geologic maps of the bedrock and surficial deposits immediately to the southeast of the Milepost 7 area. The stratigraphy, structure, and tectonic setting of the North Shore Volcanic Group and its associated intrusions, of which the rocks at Milepost 7 are a part, have been synthesized by Green (1972, 1977).

Detailed field investigations of bedrock exposures on the site were supplemented by study of the Klohn Leonoff reports and drill logs and by examination of a large number of the 73 diamond drill cores. Locations of all bedrock cores are plotted on Plate 1.

M.R. Banovetz, Executive Vice President of Reserve Mining Company, granted permission to enter the Company's lands and carry out the project. A. Samuel and P. Pastika of Reserve Mining Company also were helpful. Tom Harper, Neil Thomsen and Dan Wasylyk of Klohn Leonoff Consultants, Ltd., assisted with access to the test cores and data.

SURFICIAL GEOLOGY

Topography. The Milepost 7 area was chosen as a site for tailings disposal in part because it is a large, deep valley contained on two sides and part of a third by bedrock slopes. The east side of the valley is a rugged diabase ridge which rises about 300 feet above the flat valley floor. The northwest flank of the valley rises more gently, and is characterized by small knolls and knobs cored with diabase. Most of these knobs have distinct topographic extensions in a N. 70° W. direction, which are streamlined "tails" made of till deposited by the Superior lobe of the late Wisconsinan continental ice sheet as it moved up out of the Lake Superior basin during the Automba advance (Wright and Watts, 1969). These streamlined knobs belong to the group of drumloid features known collectively as the "highland flutes." Excellent examples are seen in secs. 22, 29, and 32.

Low, subdued hills in the southeastern part of the basin are held up by volcanic rocks which are less resistant to erosion than the more massive diabase intrusions.

The main branch of the Beaver River winds across the southern part of the map area, taking advantage of a deep gap in the high diabase ridge. The Milepost 7 valley is drained by Thirtynine Creek, a major tributary of the Beaver River. These streams have cut small channels into the Quaternary deposits and have locally reached bedrock, although not in the basin proper. The upper (northeastern) part of the basin is very poorly drained.

Direction of Glacial Movement. Glacial striations on bedrock surfaces range in bearing from N. 53° W. to due west; the average of 10 bearing measurements is N. 67° W. Along with the general N. 70° W. direction of the local topographic "flutes," the striations give a good indication of the last glacial flow direction for basal ice.

Quaternary Deposits. Pleistocene and Recent sediments cover most of the Milepost 7 area. They have been extensively sampled in pits and boreholes by the dam consultants and much information is available in their laboratory reports.

In general, the Quaternary sequence has dense, compact till at the base on bedrock; the till is overlain in some areas by well-bedded sand and gravel deposits (such as on the western slope in a gravel pit in sec. 30), which are overlain in turn by unconsolidated till. In a pit in north-central sec. 28, the sand and gravel are overlain by well-compacted till. The medial sand and gravel may have been proglacial outwash deposited during the last glacial advance. In the main part of the basin below an elevation of about 1,150 feet, red clay and silt directly overlie the basal till. These were probably deposited in a bay of Glacial Lake Duluth after the last ice had melted from the area. In the northeast end of the basin, especially in secs. 27, 28 and 33, a large and thick deposit of peat is found at the surface; smaller accumulations of peat occur in minor depressions elsewhere.

According to the engineers' test borings, the average thickness of the basal till is about 15 m, and the maximum is 33 m. Lake clays average about 4.5 to 6 m in thickness, with the greatest thickness penetrated being 14 m. Beneath the surface weathered zone, the lake clays tend to be varved, with red-brown clay laminae about 1.2 cm thick alternating with gray silty layers 2-10 cm thick (Klohn Leonoff, 1976c).

A generalized map of the surface deposits in the area can be found in Drawing 292-0024 of Klohn Leonoff's (1976d) report on surficial and bedrock geology.

BEDROCK GEOLOGY

Stratigraphy. The bedrock of the Milepost 7 area consists of volcanic rocks belonging to the Keweenawan (Late Precambrian) North Shore Volcanic Group (Green, 1972), intrusive rocks belonging to the Beaver Bay Complex, and other unnamed intrusive bodies of Keweenawan age. The main basin and the low rises in the southern part of the map area are underlain by basalt lavas, the northwest slope of the basin is underlain by diabase and gabbro sills which cut mafic lavas, and the east (Bear Lake) ridge is held up by a large diabase intrusion that contains large inclusions of metabasaltic hornfels and rarer anorthosite. The exposures in the northwestern half of the area are not good enough to define contact relations between the various intrusive units or between them and the lavas, and contacts shown on the geologic map in that area are inferred and highly generalized. Because the topographic slope of the northwestern flank of the basin is more gentle than the attitude of the basalts within it, it appears that the lavas in the basin at one time continued northwestward and overlay the intrusive rocks exposed on the northwest flank, but have been stripped off. West of the Bear Lake diabase ridge, the flows and sills strike fairly uniformly northeast and dip gently to the southeast. East of this ridge, however, in secs. 34, 35 and 36, flows strike west to northwest and dip 10° south.

The stratigraphically lowest flows encountered in the map area are fine-grained andesite, basaltic andesite, and basalt that were intersected in drill cores (D2001, D2002, and D2003) in the SE¼SW¼ of sec. 30 on the western flank of the basin. Otherwise, the bedrock of the northwest slope is known only from surface exposures, which are all of intrusive rocks. There are probably several hundred feet of unexposed volcanic rocks in between the several exposed intrusive units.

Stratigraphically above the andesite, basalt, and intrusive rocks of the northwest flank is a thick sequence of intergranular basalt and basaltic andesite that underlies the northwestern two-thirds of the main basin. These rocks are also known from drill core, principally from transects along the main dams at the southwest end (Dam 1) and the northeast end (Dam 2-3-4). Some natural exposures occur along the East Branch of the Beaver River in central sec. 22 and along the main branch in sec. 7. There are almost no data regarding dips of these lavas, but on the assumption that they have attitudes parallel to the overlying flows of ophitic olivine basalt, an estimated 210 m of lava flows are present in this group. One drill hole (4035) in south-central sec. 21 penetrated red sandstone, which is probably an interflow sand layer in this unit.

Overlying this sequence of intergranular basalt and andesite is a thick and uniform sequence of generally ophitic olivine basalt which underlies the southeastern portion of the basin and forms the low hills there. Some of these flows also crop out in the Beaver River to the south in secs. 8 and 9, and in sec. 17 directly south of sec. 8. According to their average southeasterly dip of 9°, about 260 m of ophitic basalt flows occur in this group. These appear to be traceable to the south into the Split Rock River-Gooseberry River area ("Gooseberry River basalts" of Green, 1972).

Another group of mafic lavas is found in the southeast corner of the map area. However, since they occur to the east of the big diabase dike of Bear Lake ridge (and the probable fault along which it was injected) their original stratigraphic position relative to the rest of the Milepost 7 sequence is not known. On the basis of lithologic similarity to other volcanic rocks in the Silver Bay area, they are inferred to overlie the ophitic basalts. This sequence includes at least three fine-grained flows of basalt or basaltic andesite with a total thickness of at least 15 m within the map area, and two thick flows, one of them plagioclase-porphyritic, near County Highway 4 in sec. 34.

Several blocks and slices of contact-metamorphosed volcanic rocks ranging in size from a few meters to 800 m are found within the intrusive complex of the Bear Lake ridge. Most are amygdaloidal basalt or andesite, but some are volcanic breccia or conglomerate which are commonly associated with aphanitic, light-weathering gray hornfels of uncertain but perhaps metasedimentary origin. Unmetamorphosed red interflow sedimentary rocks encountered in drill hole 5027 in a fault slice north of Bear Lake between two diabase ridges imply postintrusion faulting. The contact-metamorphosed blocks associated with the intrusive complex cannot be related with confidence to the stratigraphy of the main lava sequence of the Milepost 7 basin.

Intrusive Relations. As is common in the glaciated terrain of northeastern Minnesota, contacts between rock units are mostly hidden under surficial cover. However, a few contacts have been exposed in railroad cuts in sec. 9 and in drill cores. Topographic expression of contacts can also provide insight on intrusive relations. Structural relations of the various intrusive bodies found in the area will be discussed below, starting at the northwest corner and progressing eastward.

The hilltop in the center of sec. 19 in the northwest corner of the map is underlain by a fine-grained diabase that resembles chilled contact zones of other major diabase units in the region that are assigned to the Beaver River gabbro of Gehman (1957). No contacts with other rocks are exposed. From its broad distribution on the southeast side of the hilltop and its uniform grain size, the fine diabase is inferred to be the base of a diabase sill that dips gently to the southeast, structurally beneath a thicker sheet of gabbro which is exposed just to the east in secs. 19 and 30. The overlying sill of medium-grained to coarse-grained olivine gabbro also lacks exposed contacts and thus it could be argued that the fine diabase may be its basal contact zone. If this is so, however, the gabbro has differentiated in place because the diabase and gabbro have markedly different compositions (see table 2).

The upper contact of a very minor intrusion was cut by test hole D2003 in the SE¼SW¼ sec. 30 near Big Thirtynine Creek. The core shows a fine-grained, massive diabase or basalt chilled in sharp contact against overlying amygdaloidal basalt lava. The diabase becomes coarser and increasingly amygdaloidal downward from the contact, but the drill penetrated it for only 3 m. Two nearby drill cores, which sampled stratigraphically lower horizons, contain only lavas, so the diabase cannot be more than 10 to 30 m thick assuming the regional dip for these units.

A large olivine diabase sill with ophitic texture crops out in the Beaver River in sec. 1, T. 55 N., R. 9 W. just west of the map area, and on a series of hills trending to the northeast through the southeast half of sec. 31 to Big Thirtynine Creek. No contacts are exposed, but local subhorizontal jointing suggests a sill shape.

A distinctive sill of black, fine- to medium-grained basalt or diabase forms many natural exposures on hilltops, knobs, and the tops of east-facing slopes from the center of sec. 32 northeastward to the East Branch of the Beaver River in the northern part of sec. 21. On the basis of its topographic expression, the sill appears to have two branches. Chemically the rock is a ferrodiorite, quite distinct from other lithologic types in the Beaver Bay Complex. Jointing in a number of places suggests a sill shape, and although no contacts are exposed, a chilled basal contact was intersected by test hole 1183 near the center of sec. 32 where the sill overlies weakly amygdaloidal basalt.

A medium-grained gabbro or diabase was intersected in test hole 4037 at the northwestern end of Dam 2-3-4 and zeolitized, amygdaloidal olivine diabase was intersected in holes 3010 and 3015, farther to the southeast. However, because a typical unmetamorphosed red interflow sandstone was cored in the intervening hole 4035, it is unlikely that the diabases cut by the drilling belong to the same intrusion. There are no outcrops of these rocks in the East Branch of the Beaver River 1/2 mile along strike to the northeast. Several drill cores to the southwest in secs. 5 and 6 also encountered amygdaloidal, zeolitized diabase intrusions, none of which crop out.

The high, abrupt ridge along the east side of the Milepost 7 basin is underlain by a large intrusion of ophitic olivine diabase or gabbro. The intrusion is primarily a dike, but it is at least partly sill-like beneath southeastern extensions of the uplands. These conclusions are based on relations of mapped contacts to topography both locally and elsewhere in the Beaver Bay-Silver Bay area, on a few observations of exposed contacts, and on test drill data. The olivine diabase commonly carries xenoliths of anorthosite (Grout and Schwartz, 1939; Phinney, 1968; Phinney and others, 1979).

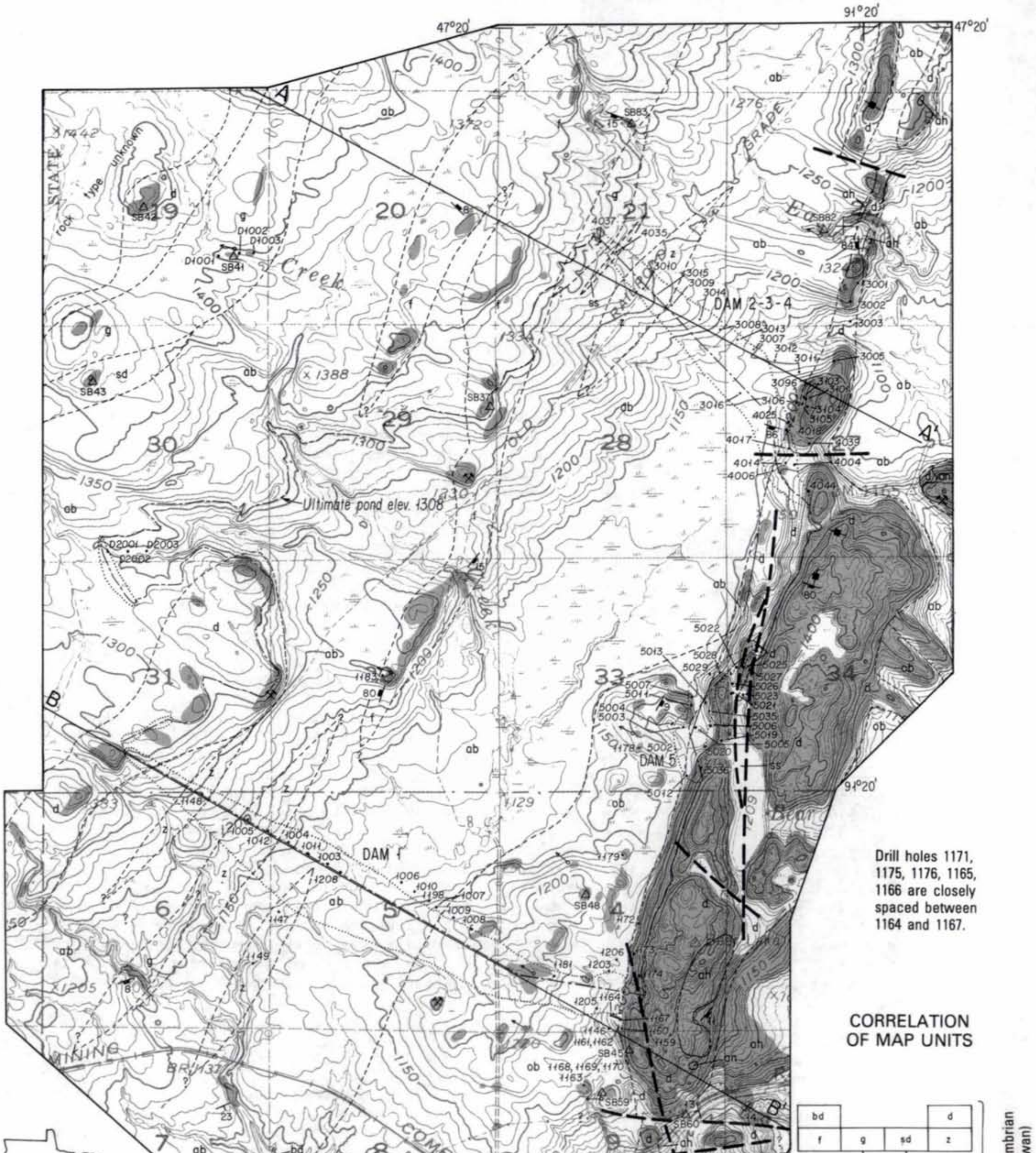
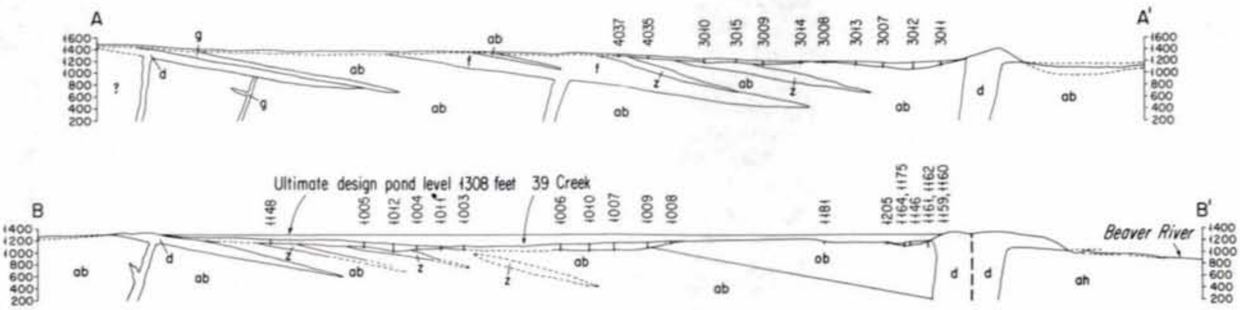

47°20'
91°20'
47°20'
STATE
rock type unknown
Creek
DAM 2-3-4
GRADE
Ultimate pond elev. 1308
DAM 5
DAM 1
MINING
COMPANY
91°20'
Drill holes 1171, 1175, 1176, 1165, 1166 are closely spaced between 1164 and 1167.
CORRELATION OF MAP UNITS
bd
d
f
g
sd
z
ah
ab
ss
ob
an
Upper Precambrian (Keweenawan)
Precambrian (age unknown)
LOCATION MAP
SCALE
N
0
1 MILE
0
1 KILOMETER

Plate 1. Geologic map of the Milepost 7 area, Lake County, Minnesota



Interpretive cross sections A-A' and B-B'. Short vertical lines are test holes drilled to bedrock with identifying numbers above. No vertical exaggeration.

DESCRIPTION OF MAP UNITS

BASALT DIKE

bd, fine-grained, black, ophitic to subophitic olivine basalt dike with chilled contacts in bed of Beaver River, east edge of sec. 7.

OPHITIC OLIVINE DIABASE

d, Gray, fine- to medium-grained; typically ophitic but finer grained varieties are intergranular to subophitic. Locally contains scattered plagioclase phenocrysts and anorthosite xenoliths. Consists of zoned plagioclase, poikilitic augite, and anhedral olivine partly altered to iddingsite, with magnetite and ilmenite and minor interstitial green chlorite and K-feldspar; apatite and quartz occur in trace amounts.

ZEOLITIZED DIABASE

z, Light-brown to tan, medium-grained, ophitic to subophitic diabase with diktytaxitic cavities. Strongly altered; some relict primary plagioclase and augite; altered olivine and opaques present, but interstitial material replaced by and cavities filled with zeolites, chlorite, and clay.

SYENODIORITE

sd, Brown, medium-grained, intergranular to subophitic rock containing andesine, clinopyroxene, partly altered olivine, ilmenite, magnetite, and apatite, with abundant interstitial orthoclase and minor quartz.

FERRODIORITE

f, Black, brown-weathering, fine- to medium-grained ferrodiorite with intergranular texture, grading to subophitic texture in coarser samples. Contains calcic andesine, clinopyroxene, altered olivine, minor hornblende, ilmenite, magnetite, and interstitial K-feldspar, quartz, and apatite. Closely resembles basalt or diabase in the field.

GABBRO AND FERROGABBRO

g, Black to medium-gray, medium- to coarse-grained gabbro consisting of plagioclase, poikilitic clinopyroxene and olivine, opaques (some skeletal), and interstitial dusty orthoclase with minor apatite, quartz, and chlorite.

ANDESITIC AND BASALTIC HORNFELS

ah, Black to dark-gray, fine-grained, more or less recrystallized lavas and minor andesitic breccia, mostly amygdaloidal. Contain plagioclase, augite ± orthopyroxene, and abundant magnetite granules ± ilmenite. Some contain abundant dusty orthoclase and minor apatite and biotite. Typically more resistant to erosion than unmetamorphosed lavas. Many outcrops show closely spaced fractures or joints. Commonly cut by veins or dikes of pale-red, fine-grained microgranite and monzonite.

SANDSTONE AND VOLCANIC BRECCIA

ss, Mostly red, fine- to medium-grained laminated sandstone, made of poorly to well-sorted, angular to subrounded clasts of more or less altered plagioclase, quartz, agate, clinopyroxene, volcanic rock fragments, and opaques in zeolite ± calcite cement. North of Bear Lake, unit includes red-brown epiclastic volcanic breccia made of aphanitic, porphyritic, amygdaloidal, andesitic to basaltic rock fragments in sandstone matrix with cement of calcite, zeolite, chalcedony, and fluorite.

OPHITIC BASALT

ob, Gray and greenish-gray, fine-grained and fine- to medium-grained basalt lavas; typically ophitic but locally intergranular or subophitic. Amygdaloidal in upper parts of flows, diktytaxitic in massive central and lower portions. Consist of calcic labradorite, augite, altered olivine, ilmenite, and magnetite, and generally an Fe-rich clay mineral (saponite?) in interstices.

INTERGRANULAR ANDESITE AND BASALT

ab, Black to dark-brown, fine-grained, intergranular to intersertal lavas with abundant amygdules. Some of the intersertal lavas have radiating, subvariolitic textures in interstitial areas suggesting quench textures. Strongly altered, they consisted originally of plagioclase, clinopyroxene, olivine, magnetite, ilmenite, apatite, and an orthoclase-rich mesostasis. Some of the basalts are plagioclase-porphyritic and some of the andesites are weakly porphyritic with small phenocrysts of plagioclase, clinopyroxene, and rare olivine. Some are also diktytaxitic with saponitic or zeolitic cavity fillings.

ANORTHOSITE

an, White, medium- to coarse-grained adcumulate anorthosite; entirely calcic plagioclase except for local minor amounts of pyroxene and olivine. Occurs as xenoliths in ophitic olivine diabase (unit d).

1178 • Location and number of test hole to bedrock

SB42 △ Location of analyzed sample other than drill core samples

85 Dip and strike of dike

6 Dip and strike of flow contact

Horizontal flow contact

80 Dip and strike of inclined joint set

Strike of vertical joint set

Direction of glacial striae

Geologic contact: observed, inferred

Inferred fault

Quarry

Prospect shaft

Ultimate planned tailings pond level

Outline of future or constructed dam

Area of bedrock exposure

The northeasternmost hill in sec. 22 is underlain by diabase except for a small cap of volcanic hornfels at the top. The diabase near the hornfels is fine grained and typical of chilled facies of these olivine diabase intrusions. This diabase body is inferred to be a sill with its roof just preserved at the hilltop; it is not connected to the main dike-like intrusion of Bear Lake ridge, but is petrologically related to it and may have been fed by it. The other hills in sec. 22 are chiefly diabase belonging to the main dike of Bear Lake ridge which is thinner here than to the south. Steep contacts against metamorphosed lavas are seen in the little canyon of the East Branch of the Beaver River.

The diabase upland begins to broaden out considerably in sec. 27, and that portion in the southeastern part of sec. 27 is thought to be underlain by a thick, subhorizontal diabase sheet. The sheet probably is not a sill in the strict sense, however, because its northeast-trending basal contact is discordant to the northwest strike of lava flows just beneath it. The western contact of the diabase is steep, as indicated by its relatively straight trend across varying topography and by drill intersections. The low area in the south-central portion of the SW1/4 of sec. 27 has no bedrock exposures. Although fine-grained diabase typical of chilled margin occurs on the small hills to the west in line with the general west edge of the large diabase dike, it is possible that the low area just mentioned could be underlain by volcanic rocks on strike with those intersected in drill holes to the south in sec. 34, north of Bear Lake. The hill east of the highway in sec. 27 is made of diabase crowded with anorthosite blocks, well exposed in a quarry on the south slope.

In the immediate area of Bear Lake, the western contact of the diabase is again rather straight, and diabase forms all of the highland. Test drill cores show the contact to be steep on the west. However, volcanic breccia and sandstone were intersected in drill holes 5023 and 5027 in the narrow valley just north of Bear Lake, and similar soft rocks may underlie the lake itself. These are at only slightly lower elevations than diabase cored just to the west in each case, and because the sandstone and breccia are unmetamorphosed, they do not appear to have been immediately beneath the base of a large sill. These observations suggest that the sedimentary rocks may be part of a slice faulted into the diabase complex at a later time.

At the southern end of the ridge in secs. 4 and 9, there is evidence for both subvertical (dike) and subhorizontal (sill) contacts. Subhorizontal columnar jointing in the railroad cut on the southeast side of the knob in the SW1/4NE1/4 sec. 9 (fig. 1) implies a near-vertical western contact for the diabase, consistent with dike form, but in the northeast end of this cut and all along the next rail cut to the northeast, lava flows underlie the diabase with a subhorizontal contact indicating a sill. The jointing in the first cut fans over to become nearly perpendicular to this subhorizontal lower cooling surface. Test drilling west of the south end of Bear Lake has established a very steep contact on the west side of the main diabase ridge. Along

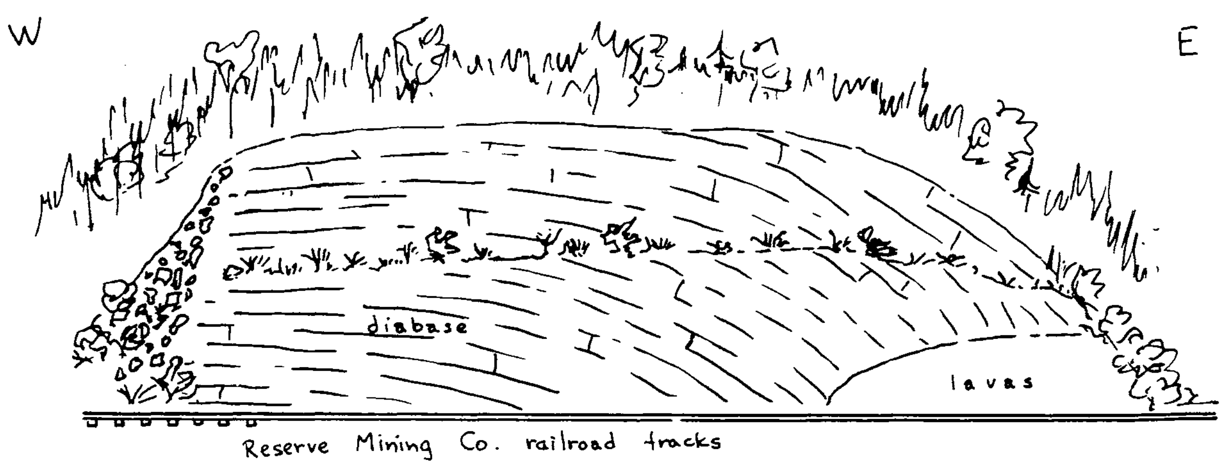


Figure 1. Field sketch of railroad cut in SW1/4NE1/4 sec. 9, T. 5 N., R. 8 W. Jointing in diabase and steep left-hand (western) slope imply a steeply dipping contact as in a dike, whereas in the east end of the cut the diabase overlies metamorphosed lavas as in a sill, with the jointing fanning over to maintain a high angle to the intrusive contact. The distance shown along tracks is roughly 150 m.

the east side of the top of the ridge is a large exposure of contact-metamorphosed basalt and/or andesite, much of it amygdaloidal. Its gross structural relations with the diabase are unknown; it may represent a large roof pendant in the sill or it may be a great xenolith. The former interpretation is preferred, since in those areas where it is exposed close to diabase, the hornfels is almost always topographically higher than the diabase.

Gehman (1957) concluded that the major body of ophitic diabase in the Beaver Bay-Silver Bay area (his Beaver River gabbro) occurs in the form of a thick sill dipping east. This probably once connected with the Bear Lake ridge diabase. In summary, the diabase complex of the high east ridge in the map area appears to consist of a large dike on the western side which merges with and probably fed a thick, gently east-dipping to horizontal sill. The sill has been largely eroded off of the Beaver River valley area just to the southeast of the Milepost 7 site.

Faults. Little direct evidence of faulting was found in rock exposures in the Milepost 7 area. A shear zone 4 to 10 cm wide striking N. 70° W. and dipping 47° NE. cuts diabase in a railroad cut in the SW1/4NE1/4 sec. 9. No measurable displacement was evident, in part at least because of a lack of marker features in the rock. Many of the test drill cores show broken and sheared zones, commonly with black chlorite and/or serpentine along them, but the test cores are not located in such a way that any actual, throughgoing major fault can be inferred. The high diabase ridge is cut by several deep gaps which are suggestive of faulting, but the rock is covered with drift in such areas, and generally the diabase on both sides is similar. Examples are (a) the north-south valley of Bear Lake and its extension to the north; (b) the N. 10° W. gap in the ridge in southern sec. 4 and northern sec. 9; (c) the northwest-trending valley crossing the ridge just southwest of Bear Lake in the NE1/4 sec. 4; and (d) the several larger gaps in the ridge in secs. 22 and 27. One gap in the SW1/4NE1/4 of sec. 22 appears to involve a major left-lateral displacement of the large diabase dike by as much as 250 m. The gap through which the Beaver River flows (sec. 9) also suggests faulting, but no displaced contacts or other evidence were seen other than the small shear zone mentioned above. The east-west trending contacts between diabase and basalt south of the river may represent either intrusive or faulted contacts.

A major preintrusion fault may be obscured by the great diabase dike that forms much of the major ridge that contains Bear Lake; in fact, the dike was probably intruded along one or more branches of this fault. The evidence for such a fault lies in the highly discordant attitude of the lava succession on the two sides of the ridge; to the east in secs. 34 and 35, the flows strike west to northwest, whereas to the west of the dike they strike uniformly northeast.

Petrology. Twenty new chemical analyses of igneous rocks from the Milepost 7 area are presented in Tables 1 and 2. These provide new compositional data on the intrusive rocks of the Beaver Bay Complex and also allow the lavas to be classified chemically and evaluated in relation to the growing body of geochemical information on the North Shore Volcanic Group (e.g., Green, 1972, 1981, 1982; Green and others, in prep.). The volcanic rocks will be considered first.

The nine lavas analyzed correspond well in both texture and composition with others described from the North Shore Volcanic Group, and range from olivine tholeiite through basaltic andesite to andesite. In general the Fe/Mg ratio, normative An content, and concentrations of incompatible elements such as K, Ti, and P all increase along that compositional trend (figs. 2 and 3). Stratigraphically, however, all of the most primitive lavas (olivine tholeiite) are from the one major unit that underlies the southeastern part of the basin and is relatively high in the local stratigraphy; thus, more "evolved" rocks underlie it and probably overlie it.

The olivine tholeiite samples are typically ophitic, nonporphyritic, and diktytaxitic. A chilled sample (SB-59), is intergranular. Their high Al_2O_3, MgO and CaO contents set these rocks off from transitional basalts and andesites (table 1). The percentages of K_2O (0.17-0.21), TiO_2 (0.89-1.37) and P_2O_5 (0.10-0.19) of these olivine tholeiites are among the lowest of any major group of analyzed Keweenawan rocks. Sample 1169-1 is intergranular but otherwise similar to the other olivine tholeiites. Its slightly higher Na_2O and TiO_2 contents may have influenced the textural difference. Chemically as well as texturally the olivine tholeiite lavas fall on a trend with the ophitic olivine diabase intrusions.

It is difficult to distinguish between nonophitic basalt and andesite in hand specimen or in thin section. As a group the basaltic andesites are lower in normative An than the olivine tholeiite-diabase series (fig. 3) and have more alkalies, Ti, and P. They can be classed as transitional or high-iron tholeiitic basalts and tholeiitic andesites. None of the samples analyzed proved to be basalts, based on normative plagioclase composition (basalt > An_{50} > andesite).

Table 1. Chemical analyses and norms* of volcanic rocks

	olivine tholeiite					tholeiitic andesite			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
SiO_2	47.95	47.60	48.15	47.05	48.15	51.55	49.05	49.90	49.45
TiO_2	0.95	0.94	1.10	0.89	1.37	2.26	3.20	3.31	3.21
Al_2O_3	16.02	16.15	16.21	16.06	16.30	13.13	12.49	11.92	12.42
Fe_2O_3	6.70	6.85	3.71	3.93	5.18	8.32	8.04	7.60	8.16
FeO	3.40	3.56	6.30	5.56	4.16	5.44	7.82	9.02	7.80
MnO	0.15	0.14	0.17	0.14	0.14	0.21	0.25	0.25	0.27
MgO	9.65	8.07	9.19	9.04	8.25	5.60	5.10	2.91	5.05
CaO	10.21	11.41	10.69	11.40	10.51	4.38	6.66	6.72	6.44
Na_2O	1.99	2.07	2.14	1.70	2.62	3.44	3.22	3.33	3.18
K_2O	0.19	0.17	0.21	0.17	0.21	2.40	1.44	1.66	1.19
P_2O_5	0.12	0.12	0.19	0.10	0.15	0.35	0.34	0.69	0.38
H_2O	2.54	1.87	1.57	2.96	2.49	2.67	2.11	2.04	2.18
CO_2	0.14	0.72	0.11	0.72	0.11	0.03	0.14	0.33	0.01
Total	100.01	99.67	99.74	99.72	99.64	99.78	99.86	99.68	99.74
Mg	0.67	0.62	0.65	0.66	0.65	0.46	0.40	0.27	0.40
An%	67	66	65	71	59	31	36	31	37
Qz	---	---	---	---	---	---	---	2.23	0.41
Or	1.12	1.00	1.24	1.00	1.24	14.18	8.51	9.81	7.03
Ab	16.84	17.52	18.11	14.39	22.17	29.11	27.25	28.18	26.91
An	34.22	34.27	34.01	35.69	32.10	13.30	15.37	12.68	16.10
Ci	12.06	13.96	14.01	12.79	15.01	5.15	12.39	12.41	11.37
Hy	21.23	19.98	17.23	23.09	12.56	25.37	20.74	20.65	25.70
Ol	7.53	5.23	9.00	4.50	9.05	2.10	3.28	---	---
Mt	1.52	1.57	1.55	1.47	1.42	2.08	2.43	2.56	2.44
Il	1.80	1.79	2.09	1.69	2.60	4.29	6.08	6.29	6.10
Ap	0.26	0.26	0.42	0.22	0.33	0.76	0.74	1.51	0.83
Cc	0.32	1.64	0.25	1.64	0.25	0.07	0.32	0.75	0.02

*CIPW molecular norms (Chayes and Metais, 1964); Fe reduced to Fe^{+3} = 0.1 Fe^{tot}
Mg number = atomic ratio Mg/(Mg + 0.9 Fe) [All analyses by K. Ramlal, Univ. Manitoba, 1979-80]

(1) Sample SB-48: Brownish-gray ophitic basalt; on knoll, SE¼NW¼ sec. 4, T. 55 N., R. 8 W.
(2) Sample SB-52: Brownish-gray ophitic basalt; north bank Beaver River, SW¼SW¼ sec. 9, T. 55 N., R. 8 W.
(3) Sample SB-59: Gray, fine-grained basalt; west side of knoll, SE¼NW¼ sec. 9, T. 55 N., R. 8 W.
(4) Sample 1178-22: Fine-grained ophitic basalt; by road, SW¼SE¼ sec. 33, T. 56 N., R. 8 W.; from 22 feet in DDH 1178.
(5) Sample 1169-1: Grayish-brown, fine-grained basalt; by road, base of slope, NW¼NE¼ sec. 9, T. 55 N., R. 8 W.; from 1 foot in DDH 1169.
(6) Sample SB-60: Dark-gray, fine-grained andesite; railroad cut, SE¼NE¼ sec. 9, T. 55 N., R. 8 W.
(7) Sample SB-82: Grayish-brown, fine-grained andesite; East Branch Beaver River, SE¼SW¼ sec. 22, T. 56 N., R. 8 W.
(8) Sample D2001-39: Dark-grayish-brown, fine-grained andesite; by Thirtynine Creek, SE¼SW¼ sec. 30, T. 56 N., R. 8 W.; from 39 feet in DDH D2001.
(9) Sample 3008-22.5: Grayish-brown, fine-grained andesite; at road, 1193 feet elevation, NE¼NE¼ sec. 28, T. 56 N., R. 8 W.; from 22.5 feet in DDH 3008.

Table 2. Chemical analyses and norms* of intrusive rocks

	ophitic olivine diabase					olivine diabase	olivine gabbro and syenodiorite		ferrodiorite			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
SiO_2	46.65	49.10	48.30	49.16	48.45	51.85	47.40	54.15	51.70	46.50	52.65	52.95
TiO_2	2.26	1.77	1.33	1.36	1.36	1.96	3.44	2.42	2.78	3.68	2.84	2.82
Al_2O_3	14.89	17.19	15.60	17.09	18.82	14.26	13.86	11.84	12.84	12.75	12.39	12.08
Fe_2O_3	3.36	2.48	2.97	2.28	1.65	2.64	6.11	6.57	4.61	10.06	4.41	4.38
FeO	10.88	9.36	8.08	7.99	8.52	7.60	9.08	8.56	10.92	7.58	10.72	10.52
MnO	0.20	0.18	0.17	0.19	0.14	0.18	0.21	0.34	0.23	0.22	0.24	0.24
MgO	7.03	4.92	8.05	7.43	6.24	5.55	4.35	2.05	3.31	4.40	3.05	3.06
CaO	9.60	10.06	10.33	10.89	10.36	10.63	10.10	6.16	6.92	8.64	6.34	7.39
Na_2O	2.26	2.75	2.17	2.35	2.51	2.88	2.40	2.99	2.77	2.63	2.59	2.38
K_2O	0.56	0.55	0.20	0.45	0.45	1.02	0.67	1.88	1.46	0.87	1.50	1.26
P_2O_5	0.28	0.25	0.17	0.13	0.17	0.31	0.31	0.96	0.56	0.43	0.64	0.42
H_2O	1.67	1.17	2.19	0.99	0.91	0.94	1.73	1.91	1.76	1.95	2.14	1.87
CO_2	0.07	0.02	0.09	0.02	0.11	0.10	0.04	0.08	0.00	0.06	0.28	0.26
Total	99.71	99.80	99.65	100.33	99.69	99.92	99.70	99.91	99.86	99.77	99.79	99.63
Mg	0.50	0.46	0.60	0.59	0.55	0.52	0.37	0.22	0.30	0.34	0.29	0.30
An%	60	59	64	64	65	49	55	35	44	48	45	48
Qz	---	---	---	---	---	1.33	0.65	9.60	5.60	---	9.36	10.32
Or	3.31	3.25	1.18	2.66	2.66	6.03	3.96	11.11	8.63	5.14	8.86	7.45
Ab	19.12	23.27	18.36	19.89	21.24	24.37	20.31	25.30	23.44	22.26	21.42	20.14
An	28.83	32.94	32.24	34.76	38.76	22.97	25.07	13.33	18.29	20.42	17.75	18.56
Ci	13.84	12.82	14.29	15.06	9.02	22.53	19.31	9.55	10.85	16.51	6.96	11.92
Hy	15.53	17.71	22.12	15.35	15.37	15.36	18.58	19.40	22.07	19.08	22.73	19.91
Ol	9.92	2.70	4.26	6.98	6.87	---	---	---	---	2.86	---	---
Mt	2.24	1.87	1.73	1.62	1.61	1.61	2.35	2.33	2.43	2.68	2.37	2.33
Il	4.29	3.36	2.53	2.58	2.58	3.72	6.53	4.60	5.28	6.99	5.39	5.36
Ap	0.61	0.55	0.37	0.28	0.37	0.68	0.68	2.10	1.22	0.94	1.40	0.92
Cc	0.16	0.05	0.20	0.05	0.25	0.23	0.09	0.18	---	0.14	0.64	0.59

*CIPW molecular norms (Chayes and Metais, 1964); Fe reduced to $Fe^{+3} = 0.1\ Fe^{tot}$

Mg number = atomic ratio Mg/(Mg + 0.9 Fe)

[All analyses by K. Ramlal, University of Manitoba, 1979-80]

(1) Sample SB-42: Gray, fine- to medium-grained, small-spotted ophitic diabase; southeast side of hilltop, SE¼NW¼ sec. 19, T. 56 N., R. 8 W.

(2) Sample SB-45: Gray, medium-grained ophitic diabase; steep slope above road, NW¼NE¼ sec. 9, T. 55 N., R. 8 W.

(3) Sample SB-88: Black, very fine grained basalt (chilled margin of diabase); East Branch Beaver River, north edge sec. 2, T. 55 N., R. 8 W.

(4) Sample GEH-1: Fine-grained border of Beaver River gabbro; Reserve Mining Company plant, east edge sec. 31, T. 56 N., R. 7 W.; from Gehman (1957, table 1, no. 1).

(5) Sample 3002-18: Gray, medium-grained ophitic diabase; near road at ridge, SW¼SE¼ sec. 22, T. 56 N., R. 8 W.; from 18 feet in DDH 3002.

(6) Sample 1167: Dark-gray, nonophitic diabase; by road, SW¼SE¼ sec. 4, T. 55 N., R. 8 W.; from DDH 1167.

Table 2. Chemical analyses and norms of intrusive rocks (cont.)

(7) Sample SB-41: Black, medium- to coarse-grained gabbro; Little Thirtynine Creek, NE1/4SE1/4 sec. 19, T. 56 N., R. 8 W.
(8) Sample SB-43: Dark-reddish, medium- to coarse-grained syenodiorite; southeast side of hilltop near southeast corner of NW1/4NW1/4 sec. 30, T. 56 N., R. 8 W.
(9) Sample SB-37: Black, fine-grained ferrodiorite; in slope, SW1/4NW1/4 sec. 28, T. 56 N., R. 8 W.
(10) Sample SB-83: Dark-brown, fine- to medium-grained ferrodiorite; East Branch Beaver River, NW1/4NE1/4 sec. 21, T. 56 N., R. 8 W.
(11) Sample 1183-6: Dark-brown, fine-grained ferrodiorite; on knoll in center sec. 32, T. 56 N., R. 8 W.
(12) Sample 1008-51.3: Fine-grained, quench-textured dike; NE1/4SE1/4 sec. 5, T. 55 N., R. 8 W; from 51.3 feet in DDH 1008.

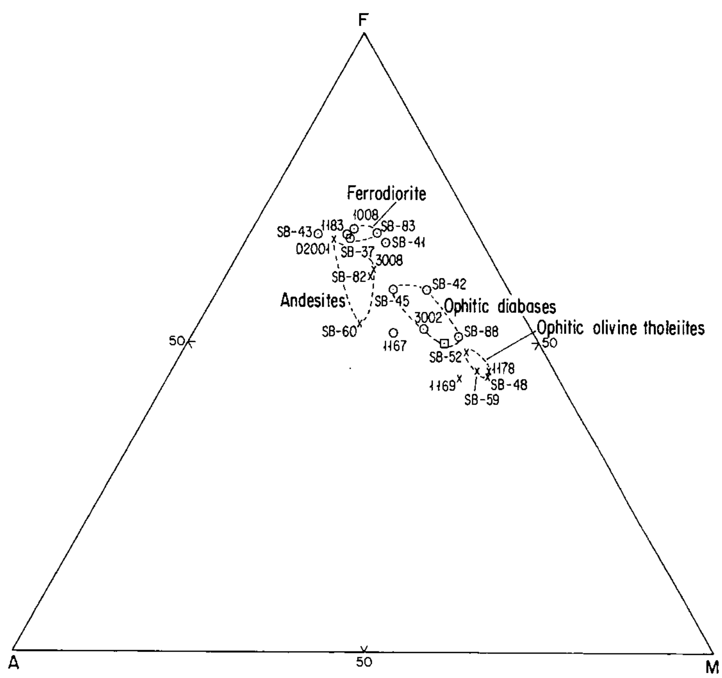


Figure 2. AFM diagram for analyzed rocks of Tables 1 and 2. Symbols: x, lavas; ⊙ , intrusive rocks; ⊡ , chilled margin of Beaver River gabbro, Silver Bay (GEH-1, table 2).

All the intrusive rocks are considered to be members of the Beaver Bay Complex as broadly defined by Gehman (1957). None of the intrusive rocks in the Milepost 7 area show evidence of cumulate origin, and all are thought to represent liquid compositions.

Four ophitic olivine diabases were analyzed (table 2). These rocks are generally nonporphyritic but some contain rare plagioclase phenocrysts. The chilled margin sample SB-88 (table 2, no. 3), which is near an anorthosite xenolith, contains scattered plagioclase xenocrysts. Chemically these rocks show a close relationship to the olivine tholeiite lavas, but have somewhat higher Fe/Mg ratios and TiO_2 and K_2O contents than the latter. They are similar to other analyzed diabases of the Beaver Bay Complex that have been assigned to the Beaver River gabbro by Gehman (1957); see Table 2, sample GEH-1 for comparison.

Not all of the rock in the largest intrusion holding up the Bear Lake ridge is ophitic olivine diabase, although that is the major lithology. A distinctive medium- to coarse-grained, intergranular olivine diabase (no. 1167) was intersected in a drill core at the base of the west slope of the ridge. The intergranular diabase has an Fe/Mg ratio comparable to the ophitic diabase, but it has a lower normative An content (49% vs 59-65%) and about twice as much K_2O (1.02% vs 0.20-0.56%). Its petrogenetic relationship to the ophitic diabase is unknown, but its composition and texture more nearly resemble those of the intergranular basalts and andesites.

One sample (SB-41) was analyzed from the coarse-grained black olivine gabbro sill in the western part of the area. It is a slightly quartz-normative ferrogabbro with a high TiO_2 content. Chemically it could represent further Fe- and Ti-enrichment along the trend of the olivine tholeiites and olivine diabase. Sample SB-43 of Table 2 is a medium-grained syenodiorite that is interpreted to be from near the top of the gabbro sill to which SB-41 belongs.

Four analyses were made of the distinctive black ferrodiorite that forms a large, two-pronged sill in the west-central and north-central part of the area and also a small dike cutting ophitic basalts in the south-central part of the area (1008-51.3). Chemically this ferrodiorite falls between the analyzed ferrogabbro (SB-41) and the syenodiorite (SB-43) but occurs as discrete intrusions.

The extrusive and intrusive rocks of the Milepost 7 area may be divided into two separate trends on the basis of texture and major-element chemistry. Chemical distinctions become less clear at higher values of SiO_2, alkalies, and Fe/Mg. The larger group contains the relatively primitive olivine tholeiite basalt and ophitic olivine diabase together with more iron-rich ferrogabbro, ferrodiorite, and syenodiorite. The other group includes intergranular basalt and andesite and an intergranular diabase. These may represent two differentiation trends, each with its different primitive parent. However, the petrogenetic relationships within each of these groups, as well as between them, are as yet obscure and await further study and evaluation. The fact that the ophitic diabases have higher Fe/Mg and Ab/An ratios than the ophitic basalts suggests that the basalt magmas were erupted relatively rapidly, with little crustal modification from their mantle origin, whereas the diabases perhaps represent magma which resided for a longer time in the crust undergoing fractional crystallization or some other mechanism of evolution before emplacement. The common anorthosite xenoliths in the ophitic diabase may be an indication of the environment in which the diabase magma evolved.

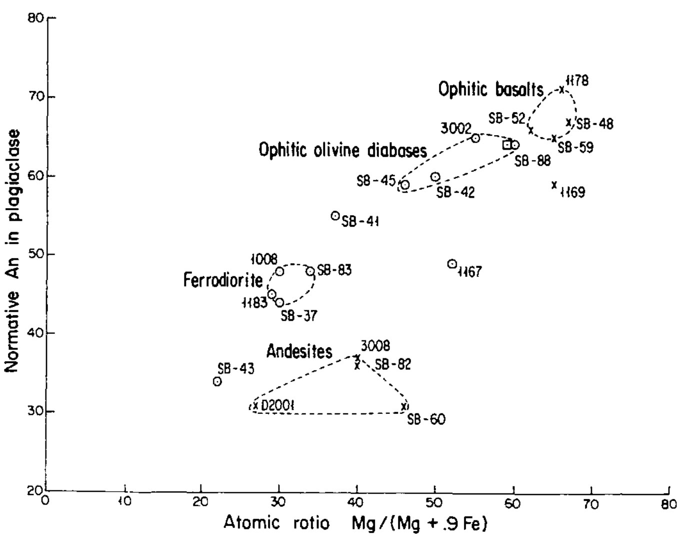


Figure 3. Plot of normative An/(Ab + An) vs atomic ratio Mg/(Mg + 0.9 Fe) for analyzed rocks of Tables 1 and 2. Symbols same as for Figure 2.

REFERENCES CITED

Arthur D. Little, Inc., 1975, Environmental report concerning on-land tailings disposal and air quality plan for the E.W. Davis works, Reserve Mining Company, Silver Bay, Minnesota.

Barton-Aschman Associates, Inc., 1975, Draft environmental impact statement, Reserve Mining Company's proposed on-land tailings disposal plan.

Chayes, F., and Metais, D., 1964, On the relationship between suites of CIPW and Barth-Niggli norms, in Carnegie Institution of Washington Yearbook 63, p. 193-195.

Gehman, H.M., Jr., 1957, The petrology of the Beaver Bay Complex, Lake County, Minnesota: Unpublished Ph.D. thesis, University of Minnesota, 92 p.

Green, J.C., 1972, North Shore Volcanic Group, in Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 294-332.

______, 1977, Keweenawan plateau volcanism in the Lake Superior region, in Baragar, W.R.A., Coleman, L.C. and Hall, J.M., eds., Volcanic Regimes of Canada: Geological Association of Canada Special Paper 16, p. 407-422.

______, 1981, Pre-Tertiary plateau basalts, in Basaltic Volcanism Study Project, Basaltic volcanism on the terrestrial planets: Pergamon, p. 30-77.

______, 1982, Geology of Keweenawan extrusive rocks, in Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America Memoir 156 (in press).

Green, J.C., Haskin, L.A., and Brannon, J.C., in prep., Geochemical character of the Keweenawan North Shore Volcanic Group of Minnesota.

Green, J.C., Jirsa, M.A., and Moss, C.M., 1977, Environmental geology of the North Shore: Minnesota Geological Survey, 99 p.

Grout, F.F., and Schwartz, G.M., 1939, The geology of the anorthosites of the Minnesota coast of Lake Superior: Minnesota Geological Survey Bulletin 28, 119 p.

Klohn Leonoff Consultants, Ltd., 1974, On-land tailings disposal study, Milepost No. 7 site: Progress Report No. 1 for Reserve Mining Company, Silver Bay, Minnesota.

______, 1975a, Design report, on-land tailings disposal, Milepost No. 7 site.

______, 1975b, Report on foundation clay disdisposal characteristics, on-land tailings study, Milepost No. 7 site.

______, 1975c, Feasibility report, on-land tailings disposal study, Milepost No. 7 site, Appendix A, Volumes 1, 2, 3.

______, 1975d, Data from May-July 1975 drilling and testing program.

______, 1976a, Data from Oct.-Dec. 1975 drilling and testing program.

______, 1976b, Data from Jan. 1976 drilling and testing program, on-land tailings disposal, Milepost No. 7 site.

______, 1976c, Engineering report on geotechnical, hydrologic, and hydraulic design for tailings disposal, Milepost No. 7 site, Volumes I, II.

______, 1976d, Surficial and bedrock geology, on-land tailings disposal, Milepost No. 7 site, for Reserve Mining Company, Silver Bay, Minnesota.

______, 1978, Data from Jan.-March 1978 drilling and testing program, Milepost No. 7 site.

Phinney, W.C., 1968, Anorthosite occurrences in Keweenawan rocks of northeastern Minnesota: in Isachsen, Y.W., ed., The origin of anorthosite and related rocks: New York State Museum and Science Service Memoir 18, p. 135-147.

Phinney, W.C., Morrison, D.A., Ashwal, L.D., and Cochran, A., 1979, Anorthosite inclusions in northeastern Minnesota: remnants of early terrestrial crust? [abs.]: Lunar and Planetary Science Conference, 10th, Houston, Texas, p. 978-980.

U.S. Army Corps of Engineers, St. Paul District, 1976, Draft environmental impact statement, proposed power plant discharge structure, delta stabilization dike and on-land taconite tailings disposal site, Reserve Mining Company, Silver Bay, Lake County, Minnesota.

Wright, H.E., Jr., and Watts, W.A., 1969, Glacial and vegetational history of northeastern Minnesota: Minnesota Geological Survey Special Publication SP-11, 59 p.