Herbert E. Wright
with the compliments
of G. M. Schwartz.

THE GEOLOGY OF THE DULUTH METROPOLITAN AREA

View of business center of Duluth, Minnesota Point, and Duluth Harbor with Superior in the background. (Photograph by courtesy Duluth Chamber of Commerce.)

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THE GEOLOGY OF THE DULUTH METROPOLITAN AREA

BY

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PREFACE

The Duluth area is one of the most interesting parts of Minnesota. It is also a critical area in determining the relationship between various rocks of Keweenawan age in the Lake Superior district. The area, therefore, has received more or less detailed study from time to time. Most of these studies, however, referred only to special phases of the geology of the region and no general description has appeared since Winchell published volume four of his final report, which contains a special chapter on the Duluth area.[1]

The object of this project was to map the metropolitan area (see Figure 1) in as much detail as practicable, accompanied by such laboratory studies as seemed desirable. This work was followed by a compilation of all available geological knowledge on the Duluth area into a readable summary for interested residents, as well as for engineers and others who need geological knowledge of the area in their work.

The field work was begun in 1937, and the major portion of the field seasons through 1940 was spent in the Duluth area and adjacent portions of the region. Other projects, mostly a result of the war, interfered with the completion of the field work and compilation of the results.

The writer is indebted to many persons for innumerable courtesies during the work. The engineering staffs of St. Louis County and the city of Duluth furnished maps and information that aided greatly in the work. Dr. A. E. Sandberg and Mr. Ray Knutsen each served as field assistant for two years and much of the credit for the field work is due to them. Dr. Sandberg had previously spent a great deal of time on field work in connection with a thesis presented to the University of Cincinnati. Professor Thomas W. Chamberlin of the University of Minnesota, Duluth Branch, kindly prepared the chapter on economic geography which is published under his name.

The writer is especially indebted to his colleague, Professor Frank F. Grout, for continued suggestions and advice.

GEORGE M. SCHWARTZ

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ABSTRACT

The Duluth metropolitan area consists of a triangular region of approximately 750 square miles in northeastern Minnesota. The topography is characterized by a long bluff overlooking Lake Superior and extending the length of the city and beyond. Inland the area has the rolling topography characteristic of much of the Superior upland. The location of Duluth and Superior, Wisconsin, at the head of the Great Lakes has been an important geographic factor in the development of the area and in present-day economic activities (discussed by Professor Chamberlin in the chapter on geography).

The formations exposed in the area include the Thomson formation probably of Knife Lake age, the Puckwunge formation correlated as Lower Keweenawan, and the Keweenaw Point volcanics, Duluth gabbro, and Beaver Bay complex of Middle Keweenawan age, overlain by the Fond du Lac beds of the Upper Keweenawan. Spread unevenly over the older rocks is a mantle of Pleistocene deposits.

The Thomson formation consists of beds of slate and graywacke probably more than 20,000 feet in thickness. The beds have been compressed into a series of folds that strike east–west. The Puckwunge formation consists of conglomerate and sandstone beds about 200 feet thick that lie on the eroded Thomson beds with marked structural discordance.

The earliest known lava flow of the region lies on the sandstone without visible discordance. The lava flows of the Duluth region aggregate more than 20,000 feet, consisting mainly of basalt but including some thick rhyolite flows. A small part of the flows lies beneath the Duluth gabbro and metamorphism of the flows above and below is pronounced.

The gabbro and some of the diabase sills have a red granite segregate at or near the top. Intermediate kinds of igneous rocks such as syenite and diorite are completely lacking.

The geologic structure of the region is dominated by its position on the north limb of the Lake Superior syncline. However, the complex structure of the slates and graywacke beds of the Thomson formation is older in origin and has little direct relation to the Lake Superior structure. The structure of the lava flows was greatly disturbed near the contacts by the intrusion of the Duluth gabbro and the numerous sills and dikes of the Beaver Bay complex.

The origin of Lake Superior is believed to be mainly a result of scouring by successive ice lobes that occupied the synclinal basin.

The glacial deposits were formed by the Superior lobe of the late Wisconsin glaciation. Of special importance are shore features and deposits

of glacial Lake Duluth and other stages of the glacial lake that occupied the Superior basin.

Economic deposits and problems discussed include clay, building stone, crushed rock, gravel, titaniferous magnetite, copper explorations, water supply, and foundation conditions.

CHAPTER I

GENERAL FEATURES OF THE REGION

The Duluth metropolitan area, for the purpose of this report, consists of a triangular region extending from Duluth northeast along the shore of Lake Superior to Two Harbors; thence due west along the line between Tps. 52 and 53 N. to the west side of R. 17 W.; thence south to Atkinson and east to the Wisconsin state line (Figure 1). This embraces the various survey townships from 48 to 52 N. and from R. 11 W. to R. 17 W. The total area is approximately 750 square miles.

The ninety-second degree meridian passes through the area about at the east city limits. The forty-seventh parallel of latitude passes a short distance south of Two Harbors and across T. 52 N.

The area, together with that of Superior, Wisconsin, forms the southwest end of Lake Superior, often referred to as the "Head of the Great Lakes." Most of the area described lies on the northwest shore of the lake. For convenience this is usually referred to as the "North Shore" by residents of the area.

Topography

The surface of the Duluth area is one of considerable contrasts. The most striking feature is the bluff which overlooks the basin of Lake Superior. The average height of this bluff is about 500 feet, but it varies considerably. The tops of many hills reach an elevation of 1300 feet within 2 miles of Lake Superior, which has an average elevation of approximately 602 feet. Elevations of 1400 feet occur within 3 miles of the lake and the maximum elevation within Duluth is in the northeast quarter of Sec. 5, T. 50 N., R. 14 W., where a small hill reaches 1481.7 feet above sea level or 880.1 feet above Lake Superior. The maximum elevation on the Duluth topographic sheet is just above the 1520-foot contour in Sec. 32, T. 51 N., R. 14 W., less than a mile north of the highest point within the city.

The bluff or escarpment, so conspicuous from New Duluth eastward beyond the downtown section, is not typical of the north shore in general. It is higher and more abrupt owing to the massive gabbro, which has resisted erosion. It is noteworthy that this highest portion of the escarpment turns inland in conformity with the top of the gabbro. The bluff does not, however, follow the contact but is determined by the baked and hardened lava flows immediately above the gabbro. The highest portion of the ridge trends somewhat inland to Woodland Park and eastward in Sec. 1, T. 50 N., R. 14 W., where its continuity is broken by the valley of Amity Creek. To the eastward a prominent ridge intervenes and deflects

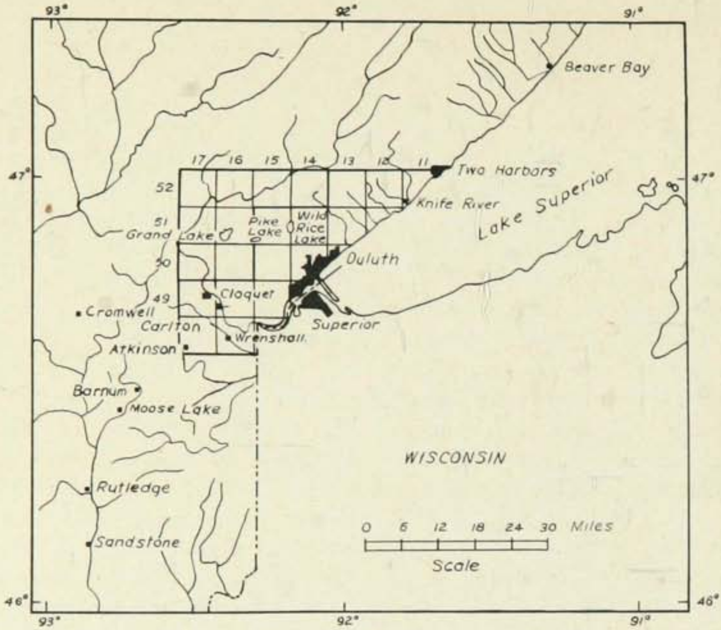

FIGURE 1. — Key map showing Duluth metropolitan area and adjacent area.

Amity Creek northeastward. This ridge is formed by the resistant rocks of the Northland sill, a somewhat irregular intrusive whose general extent is shown on the maps accompanying this report. (See Plates 1 to 19.)

At Lester Park and beyond, there is a decided gap in the bluff where East and West Amity creeks join to form the West Lester River, which in turn joins the East Lester River near Lake Superior. East of the Lester River another diabase sill trends inland, forming a prominent ridge at a considerable angle to the shore. It is accordingly true that there is no real bluff or escarpment east of the city limits as far as Two Harbors. The rise to the upland is gradual and takes place over a distance of several miles.

The upland of the area has the typical features of the various types of glacial deposits which form a cover over much of the region. Ground moraine areas have a gently rolling topography with relatively large areas of level swamp land (Figure 2) between the irregular, low hills. Terminal moraine areas are much more hilly with well-developed knob and sag topography at many places.

Lake Superior occupies a great depression or basin which extends far to the southwest of the present lake. On the Minnesota side the edge of the basin is close to the present lake, but on the south shore in Wisconsin the escarpment is far from the lake. Farther south in Minnesota the de-

FIGURE 2. — Typical muskeg swamp on the glaciated Superior upland of the Duluth area.

pression extends to the southwest up the present valley of the Nemadji River and on to Moose Lake (Figure 1).

Much of the area described is drained by the St. Louis River, which flows as a sluggish stream across the upland. At Cloquet the river has cut down to the slates, and doubtless these rock ledges have ponded the river above, giving it a low gradient. From Cloquet downstream, however, the river has a series of rapids and falls, and the drop is rapid to the foot of the lower dam above Fond du Lac.

Numerous small streams drain much of the area close to Lake Superior so that no stream has a large drainage basin. Some of these streams drain a small area of upland. The tributaries of these streams have a low gradient, but over much of their course they have a steep gradient and have cut down to solid rock. In most cases the streams have just worked down to the rock surface or cut only a small gorge. Locally, mainly near the lake, picturesque gorges have been eroded, but the relatively recent establishment of the present level of Lake Superior has not permitted much erosion.

The Minnesota coast of Lake Superior in a general way is remarkably regular. This has been suggested as evidence of a fault, but such a conclusion, at least in so far as it is based on topography, is very dubious. It is more likely that the relative regularity of the shore is a result of the gentle dip of the beds toward the lake but at a small angle to the shore. If the coast, or the maps accompanying this report, are examined in detail, it will be found that the irregularities of the coast are closely adjusted to the character of the rock. The most prominent projection is Stony Point, southwest of Knife River (Plate 13). This is formed by a massive diabase intrusive. To the east, Knife Island is composed of the same rock. The bay behind Knife Island, however, is eroded in flows which are generally somewhat softer. In detail along shore soft amygdaloidal zones form small coves with the main portion of each flow forming a point (Figure 3). This tendency is particularly well shown along East Agate Bay at Two Harbors.

Lake Superior deepens very quickly along the north shore. At Duluth, however, outside Minnesota Point, the lake has been filled in by extension of the deposits of the St. Louis River and other streams. Maximum depth opposite Duluth does not exceed 25 fathoms (150 feet).

FIGURE 3. — View of typical coast line formed by erosion of lava flows. Cove and spur effect, a result of successive flows.

Northeastward from Duluth to Knife River and Two Harbors, the lake deepens rapidly, reaching a depth of 90 fathoms (540 feet) at a point 3 miles offshore from the mouth of the Knife River. Opposite Two Harbors the maximum depth is 116 fathoms 4 miles offshore. All along this area the depth decreases from points 3 to 4 miles offshore to the Wisconsin shore.

One of the most interesting features of Duluth topography is Minnesota Point with its counterpart, Wisconsin Point. (See the Frontispiece.) Minnesota Point extends out from the north shore for a distance of 7 miles, and Wisconsin Point more than 3 miles from the south shore. Only a relatively narrow channel is maintained between them, and long breakwaters extend out into the lake to furnish a safe entry for the great ore carriers and other ships. The entrance at the Duluth High Bridge is a canal excavated across the sand bar. These great points are properly referred to as spits. If they had connected, completely separating St. Louis Bay from the main lake, a bar would have resulted. These spits have been built up by a combination of wave action and shore currents, aided no doubt by sediment added during the early postglacial history of the St. Louis River.

The southwest end of Lake Superior is relatively shallow as a result of the extension of the St. Louis River delta into the lake. Because the lake is shallow the waves have dragged on the bottom, breaking and churning up the sand and heaping it up in the shallow water.

The prevailing winds on Lake Superior are from the northeast so that southwestward-flowing currents have been set up, particularly along the north shore. As these currents strike the points, they are deflected, lose velocity, and deposit their sediment. Observations along the present point suggest that wave action is of greatest importance.

FIGURE 4. — Sand dune, Minnesota Point.

Back of Minnesota and Wisconsin points an earlier pair of shorter points (Rice's Point and Connor's Point) were built in the same way only to be isolated from the main lake by the formation of Minnesota and Wisconsin points, probably as a result of shallowing water due to deposition of sediment.

Minnesota Point is about 1000 feet wide at its base but from 300 to 500 feet wide on the average over its length. The surface is made up mainly of sand dunes (Figure 4) heaped up by the strong winds blowing in from Lake Superior. Its outer portion is partly covered by a beautiful pine forest.

The valley of the St. Louis River from Fond du Lac to Minnesota Point presents interesting problems which may be briefly noted. Available data indicates that a considerable area at the head of Lake Superior has been filled in by glacial lake and alluvial deposits of the St. Louis and other rivers, especially the Nemadji. Leverett shows that some of the moraines in this area were laid down in water ponded in front of the Superior ice lobe. It has been suggested by Martin that during late glacial time the present St. Louis River developed into a meandering stream with a wide flood plain.[1] This stream cut rather deeply into the lake clay plain. Later, the valley was drowned as far up as Fond du Lac by postglacial tilting, which has resulted in depressing the southeast end of Lake Superior, partly flooding the valley. For a detailed description of the glacial history of Lake Superior, the reader is referred to Leverett's *Moraines and Shore Lines of the Lake Superior Region*, Professional Paper 154-A of the United States Geological Survey.

CLIMATE[2]

The climate of the Duluth area is continental, modified somewhat by the presence of Lake Superior. The effect of the lake, comparatively great near the shore, fades rapidly away from the lake, particularly past the bluffs that parallel the lake. Continental climates are characterized by greater temperature extremes and a lesser rainfall and humidity than areas near the oceans.

Lake Superior modifies the extremes of temperatures considerably. The mean temperature for January along the coast is a full 10° above that of the Red River valley in northwestern Minnesota. In July, the mean temperature for Duluth is several degrees below that of Minneapolis and St. Paul.

The average temperature at Duluth for a period of 71 years is 38°: the highest temperature, 106°, was recorded in July 1906, and the lo· est, — 41°, was recorded in January 1885. The average precipitation ᶠ 75 years is 27.94 inches. This is practically the same as that of Minneapolis and St. Paul, indicating that Lake Superior does not tend to increase precipitation to a significant extent. The minimum rainfall for any year since 1871 was 18.11 inches in 1911. The highest rainfall was 45.28 inches in 1879. The average snowfall is 54.7 inches. The average percentage of possible sunshine is 53. The prevailing wind is from the northe·st

The average date of the last killing frost in spring is May 8 and of t..e first killing frost in autumn, October 5. These dates apply only to Duluth. They would change considerably if reported for the entire Duluth area as described in this report. Killing frosts occur later in spring and earlier in autumn as distance from the lake is increased. The average duration of the growing season is 150 days at Duluth; it becomes shorter as the distance from the lake increases. The longest growing season recorded at Duluth was 192 days in 1880 and the shortest 110 days in 1917.

[1] Lawrence Martin in *The Geology of the Lake Superior District* (United States Geological Survey Monograph 52, 1911), p. 456.

[2] The data for this section has been supplied by H. G. Carter, meteorologist, Weather Bureau, United States Department of Commerce, Duluth, Minnesota.

CHAPTER II

ECONOMIC GEOGRAPHY

BY THOMAS W. CHAMBERLIN

By virtue of their geographical situation (Figure 1), Duluth, Minnesota, and Superior, Wisconsin, should be considered as a single metropolitan area. Although their terrain differs markedly, the chief functions of both cities are to export iron ore and wheat and to import coal for the region surrounding the western borders of Lake Superior. Because of the geographical limitations imposed by this bulletin, only the Minnesota areas will be described except for the joint commercial activities of the two cities.

Growth Factors and Land-Use Pattern

Although many factors have contributed greatly to Duluth's present size and importance, no factor has contributed more than its location at the head of the Great Lakes. Even before white men arrived in this region, the Indian name for Duluth's site was *Onigumins,* meaning "Little Portage." The name referred to the fact that it was customary for Indians making the traverse between Lake Superior and the St. Louis River to portage across the narrow spit, now known as Minnesota Point (Frontispiece), instead of making the long tour around to the natural bay entrance 6 miles to the southeast.

Since 1856, when the first townsite was platted, Duluth has attained a population of approximately 105,000 and a land area of 62½ square miles. This growth has been the result of many favorable natural and human factors. In addition to its location at the head of the lakes and a deep, well-protected harbor with a broad river lowland leading in from the southwest, Duluth has three of the richest iron ore deposits in the United States within a distance of 110 miles, many hydroelectric power sites on nearby rivers, a rich agricultural hinterland to the west, many nearby lakes and forested areas, a cool summer climate, the pure cool water of Lake Superior, and a scenic view from hillsides bordering the lake. The human factor is its intelligent and energetic population, descended largely from Scandinavian and other North European peoples.

Duluth's pattern of urban land use is influenced greatly by the city's hillside site, which slopes gradually upward for a short distance from the waterfront and then steepens abruptly for a distance of approximately 2 miles to the uplands 600 to 700 feet above the lake level. This slope is traversed by twelve major streams whose valleys, in many cases, have been left in their natural state and are used as parks and green belts between the variously defined neighborhoods (Plate 11).

Most of Duluth's commercial and heavy manufacturing activities occupy relatively flat areas bordering the shorelines of St. Louis River, St. Louis Bay, Rice's Point, Duluth Harbor Basin, and Minnesota Point. (See Plates 8 and 11.) Because of the restricted width of the coastal plain along Lake Superior's shoreline northeast of Minnesota Point, one railroad line is the only important commercial activity along the lakeshore. Lighter types of manufacturing and wholesale and retail stores occupy a rectangular area, approximately 5 blocks up the hillside and 20 blocks long, whose base is centered at the "foot" of Minnesota Point. Although the downtown or commercial core area is between Fifth Avenue East and Fifth Avenue West along Superior and First streets, which parallel the shoreline, retail establishments are located northeastward for about a mile along Superior Street and southwestward intermittently for approximately 5 miles along Superior Street and Grand Avenue.

In general, Duluth's best residential districts are northeast of Eighteenth Avenue East. Absence of possibilities for industrial and commercial activity in this section and a view of the lake have, for many years, attracted builders of the more expensive residences. In common with other cities of comparable size, Duluth has a fringe of "blighted" or rundown residences adjacent to its retail-wholesale core. Middle and low class housing is characteristic of areas inland and southwest of the commercial core. This results from a general desire of workers to live near their places of employment, in this case the industrial and commercial districts bordering the river and bays.

Fourteen per cent of the city's 40,073 acres is maintained as parks or municipal forest. Ninety-eight well-scattered parks and recreation areas within the city limits have a total of 3567 acres. Many of the parks cross the city at right angles along the valleys of the small streams, which are poorly suited for any other type of use. Five municipal forests include an additional 2149 acres, making a total of 5716 acres. The city also has title to 528 acres of forest outside the city limits. The Skyline Drive along the upper crest of the hillside gives local residents and visitors a view overlooking most of the city and its adjacent water bodies.

Duluth's excellent harbor facilities are of prime importance to her economic welfare. Duluth-Superior harbor consists of (1) an outer bay between Minnesota Point and Rice's and Connor's points, (2) St. Louis Bay extending upstream to Grassy Point, and (3) the dredged portions of St. Louis River to Spirit Lake. For commercial purposes the outer bay has four designated parts in the following order from northwest to southeast: (1) Duluth Harbor Basin (446 acres), (2) Superior Bay, (3) Superior Harbor Basin (290 acres), and (4) Allouez Bay. St. Louis Bay is dredged and its shores are well occupied by docks. The St. Louis River portion of the harbor has not been utilized to any great extent. In the three har-

FIGURE 5. — View of a portion of Duluth Harbor with the business center in the background. (Photograph by courtesy Duluth Chamber of Commerce.)

bor areas are 49 miles of harbor frontage, of which only 6.7 miles are occupied by wharves. Seventeen miles of channels have been dredged to serve this frontage. The one hundred and ten harbor terminals include seven iron ore docks, nineteen coal docks, and thirty grain elevators (Figure 5). Duluth's two iron ore docks border St. Louis Bay; Superior's five ore docks face the Superior Harbor Basin opposite the Superior entry.

Economic Activities

Thirty-three American companies operate 393 boats in the interlake service from Duluth-Superior during an average navigation season of 232 days between April 23 and December 10. Four Canadian companies operate an additional 76 boats that serve this port. In a normal season these boats make about 7000 arrivals and departures. Packet service was discontinued during World War II but may be resumed on the Great Lakes in the near future.

The port of Duluth-Superior is served by eight trunk line railroads. Six railways have terminal facilities in the two cities: (1) Northern Pacific Railway, (2) Duluth, Missabe, and Iron Range Railway, (3) Great Northern Railway, (4) Minneapolis, St. Paul, and Sault Ste. Marie Railroad, (5) Duluth, Winnipeg, and Pacific Railway, (6) Duluth South Shore and Atlantic Railway. In Duluth, the Duluth, Missabe and Iron Range operates two ore docks. The Northern Pacific operates four ore docks and the Great Northern operates one in Superior. The Duluth, Missabe and Iron Range also has the only ore docks at the port of Two Harbors 26 miles northeast of Duluth.

Eighteen truck lines operate out of Duluth. The Williamson-Johnson airport is situated 6 miles northwest of Duluth's downtown civic center (Plate 12). This airport occupies 1020 acres and has 3 major runways. Northwest Airlines, Trans-Canada Airlines, and Wisconsin Central Airlines use the field. Private hydroplanes operate from a base on Minnesota Point.

Duluth-Superior has ranked second to New York in tonnage of waterborne commerce for many years. In the peak year of 1942, total harbor commerce was 74,314,646 tons. Average annual tonnage for the ten-year period from 1937 to 1946 was 57 million short tons. The overwhelming predominance of iron ore in this commerce is shown by the following analysis of shipping statistics for the year 1946.[1] Total shipments from Duluth-Superior in 1946 were 42,242,033 tons with the following breakdown in percentages: iron ore, 91.3, wheat, 6.9, oats, 0.4, unmanufactured iron and steel, 0.4, flaxseed, 0.4, other shipments, 0.6. Receipts at the twin harbors were of a greater variety with coal, limestone, and gasoline comprising the bulk of incoming tonnage. Total receipts in 1946 were 12,043,352 tons with the following breakdown in percentages: bituminous coal, 78.5, limestone, 5.7, anthracite coal, 5.3, gasoline, 4.9, fuel oil, 1.4, barley, 0.7, grain screenings, 0.5, gravel and sand, 0.4, others, 2.6.

Of the total tonnage in 1946, excluding bunker coal, 31,292,296 short tons passed through the Duluth canal, and 22,957,914 short tons passed through the Superior entry.

In terms of tonnage coal is the leading item distributed to Duluth's hinterland. Because of the need for ballast by lake freighters hauling iron ore, the freight rate for coal is only 65 cents per short ton compared with a shipping rate of 89 cents per short ton for iron ore and $1.66 per short ton of wheat carried to the lower-lakes ports. Of the 9,696,941 tons of coal unloaded at Duluth-Superior docks in 1947, a large percentage was moved to inland regions by rail or truck, illustrating the "break-bulk" character of the twin harbors' commerce.

The relatively low percentage of employees in transportation and utilities activities indicates a high degree of mechanization in handling such large quantities of iron ore and coal. Railroad employees made up 43 per cent of the total workers in this group in 1940.

Percentage of employment gives an indication of relative importance

[1] Source data concerning shipments and receipts was taken from *Statistical Report of Marine Commerce of Duluth-Superior Harbor for the calendar year 1946* (Corps of Engineers, War Department), p. 4.

of a city's functions. The accompanying table for the years 1940, 1946, and 1947 shows an increasing importance in manufacturing.

Because lake shipping ceases in early December, maximum employment is ordinarily above the annual average in September, October, and November. Minimum monthly employment is often experienced in February, March, and April.

EMPLOYMENT IN MAJOR OCCUPATIONAL GROUPS, DULUTH, MINNESOTA

Group	1940*		1946†		1947†	
	No.	Per Cent	No.	Per Cent	No.	Per Cent
Manufacturing	5,453	17	9,263	25	11,249	28.0
Retail and wholesale	9,291	29	10,297	28	10,615	26.5
Transport and utilities	4,475	14	6,563	18	6,695	16.5
Service and miscellaneous	4,770	15	4,916	13	4,968	12.5
Government	1,773	6	3,036	8	3,210	8
Construction	1,529	5	1,605	4	1,954	5
Finance, insurance, and real estate	1,390	4	1,478	4	1,404	3.5
Personal services	3,382	10	....‡	..‡	....‡	..‡
Mining§	257	..				
Agriculture, forestry, and fishing	264	..	....‡	..‡	....‡	..‡
Totals	32,584		37,158	..	40,095	

* The data for 1940 is taken from the *1940 Census of the United States,* II: 70.

† The data for 1946 and 1947 is based on information supplied by the Duluth office of the Minnesota State Employment Service. The employment office tabulates only the totals for each month. These were averaged by the author to obtain the 1946 and 1947 numbers and percentages.

‡ Since employment figures obtained from the employment office are based solely on social security payments, the self-employed, unpaid family workers, and domestics in private households could not be included for 1946 and 1947.

§ Mining employees are included under "Service and miscellaneous" for the years 1946 and 1947.

The year 1947 was the first year since the early 1920's in which manufacturing employment exceeded that in the retail-wholesale business. Whether this will continue in the future is a matter of conjecture. A study of the city's past history in this respect indicates that Duluth's eccentric position in relation to the country's major markets makes it difficult, under ordinary circumstances, for Duluth factories to compete with those in the lower-lakes manufacturing belt. In the 18 months before January 1, 1948, 81 new enterprises were established in Duluth, providing 2722 new jobs and adding more than $9,000,000 to payrolls.[2] A wide variety of articles is produced or processed by the 229 manufacturing plants listed in the 1947 Duluth Chamber of Commerce Industrial Directory. All together, 104 classes of manufactured articles are produced in these plants. Some of the more important enterprises are these: 25 printers, 23 grain elevators, 17 creameries, 16 forest product plants,

[2] *Duluth News Tribune,* January 1, 1948, p. 13.

12 iron and steel fabricating plants, 1 iron and steel plant, 2 blast furnaces, 2 ship builders, 1 telephone switchboard factory, 7 clothing factories, 7 furriers, 6 farm feed plants.

Employment by these factories ranges from one plant (American Steel and Wire Company) with more than 2500 workers to 204 firms which employ fewer than 100 workers each. Comparison with an earlier industrial directory shows that 78 of these 229 firms were in existence in 1925.

Factors contributing to the recent industrial growth of the city include (1) much available manufacturing space in the form of buildings already constructed; (2) much highly productive and easily trained labor; (3) the post-World War II expansion of markets; (4) low-cost power sources; (5) unlimited supply of soft water; and (6) good labor-management relations in the area. In July 1946, 1¼ million square feet of manufacturing space was available in the city. On January 1, 1948, only 100,000 square feet of such space remained unoccupied. Further industrial expansion will necessitate additional building despite the present high cost of construction.

Low-cost electric power sources have aided Duluth's industrial growth. Electricity for the area is provided by an interconnected system of twelve hydroelectric and four steam-electric plants. Hydroelectric plants with a capacity of 95,036 kilowatts are located at dams along the St. Louis River, the Kettle River, and Upper Mississippi River tributaries within a radius of 140 miles of the city. New generators at the nearby Thomson plant will provide an additional 11,900 kilowatts by 1949. The steam-electric plants have a capacity of 60,900 kilowatts and will be supplemented by a new plant in Duluth which will produce 32,850 kilowatts by 1950. Need for additional power plants was brought about by an increase of 20 per cent in the 1947 electric power requirements over the 1946 figure.

Because of the low shipping costs for coal, manufactured gas is relatively inexpensive in Duluth. The gas is purchased from the Interlake Iron Corporation, but the service is operated by the city. Annual consumption approximates 1.4 billion cubic feet of this coke-oven gas.

Duluth's water supply is pumped from Lake Superior at Lakewood by a municipally operated plant. Nearly 5 billion gallons are used annually. Lake water enters the city mains at an average temperature of 39° F. (in September, at 51°; in April at 32°). Total hardness of the water is 54 parts per million. Its alkalinity as calcium carbonate is only 43 parts per million. A city sewage disposal department is maintained by charges based on the amount of water metered into each residence or place of business. The disposal plant empties its purified water into St. Louis Bay at Twenty-fifth Avenue West.

Retail-wholesale activities had the second largest group of employees in the city, a result of Duluth's location at the head of the lakes, focal position in relation to railroad lines, and large size in comparison with cities to the west. In December 1946 there were 7331 retail employees and 4468 employees in the wholesale trade business.[3] These employees worked for 235 wholesale and 719 retail concerns.

The wholesaling of hardware, groceries and food products, and drugs, in the order named, makes up the greater share of Duluth-Superior wholesale trade. The wholesale hardware trade area served by two Duluth wholesale hardware houses covers Upper Michigan, the northern two thirds of Wisconsin, most of Minnesota, all of North Dakota, the northern two thirds of South Dakota, most of Montana, and the northern part of Wyoming.

The tourist industry is relatively important to Duluth during the summer months, but no statistics have been tabulated to indicate the exact value of the tourist trade to the city. An estimated 300,000 persons visited the city in 1947, adding a flow of approximately $4,000,000 to the trade channels of the city. Many of the tourists were overnight visitors on their way to hunting, fishing, and other recreation areas north of the city. Others come to the city for relief from hay fever and the hot summer weather of regions to the south.

In summary, Duluth is a break-bulk shipping center for the region's iron ore, wheat, coal, and wholesale trade because the city has an excellent harbor and is at the westernmost end of the Great Lakes. Local industries have developed in response to low-cost power sources, an unlimited supply of soft water, and certain favorable economic factors. Wholesale trade is important here because of an early start and a lakehead location between manufacturing centers of the East and a large agricultural market to the west. Although winters are severe because of the high latitude and travel within the city is sometimes difficult because of steep grades, the cool pleasant summers attract thousands of visitors who add to the city's income.

Two Harbors and Cloquet

The small port city of Two Harbors (Agate Bay), located 26 miles northeast of Duluth (Plate 17), probably exports more tonnage per inhabitant than any other port in the world. In 1945 this city of 4046 population ranked thirteenth in tonnage among all ports in the United States and fifth in tonnage among all Great Lakes ports. In 1946 its interlake traffic included 15,443,331 tons of iron ore shipments and 200,473 tons of coal receipts. Local traffic was composed of 30,415 tons of bituminous coal (dumped into bunkers of vessels for fuel) and 16 tons of fish.

As indicated by its common name, Two Harbors has two natural harbors, Agate Bay and Burlington Bay. Agate Bay is three quarters of a mile long in an east-west direction and half a mile wide. The harbor improvements are two breakwaters, three iron ore docks, one merchandise

[3] *Tenth Annual Report to the Governor on the Administration of the Minnesota Employment and Security Law*, p. 56.

wharf, one coal dock, and one tug wharf. Burlington Bay is not used. All railroad facilities and docks are owned and operated by the Duluth, Missabe and Iron Range Railroad. There are no other large commercial or manufacturing activities in the city.

Cloquet (population 7304) is located on St. Louis River 18 miles southwest of Duluth (Plate 10). This city has adjusted its economic activities to a changing supply of natural resources in the adjacent area. Formerly surrounded by extensive forests of white pine and other softwoods, Cloquet was primarily a saw mill center. When a forest fire destroyed the town and much of its timber supply in 1918, the citizens rebuilt the town. Its industries began to find new uses for second-growth timber of lower quality. Since that time, three local companies have successfully manufactured such products as wood pulp, paper, flexible insulation, rigid insulation, decorative insulation board, bulk insulation, felted wood fiber blanket, matches, and clothespins.

In 1947 the three companies employed a total of 3097 people and used 251,657 cords of wood. Much of the cordwood is produced by Minnesota farmers; the rest is either purchased from contractors or cut from lands owned by the mills. One company alone uses approximately 2 billion gallons of water annually from the St. Louis River, afterward returning the water to the river. Coal used in the companies' power plants is shipped from the nearby coal docks in Duluth. In 1947 the production of finished materials totaled 148,300 tons in addition to approximately 700,000 cases of matches and 150,000 cases of clothespins.

Agriculture

The rural population of the Duluth metropolitan area is employed in both urban and agricultural activities.[4] North of Duluth, 75 to 80 per cent of the employed population living outside the city limits commutes to work in the city. Agricultural production of the area shown in Plate 4 is concerned primarily with dairying and secondarily with truck farming. The major feed crops are oats, barley, fodder corn, timothy, alfalfa, and clover. Creameries are common in most of the small towns within a 50-mile radius of both Duluth and Superior. Atkinson Township (population 286) has attained national prominence as a Guernsey cattle center.

Vegetables produced commercially in the area include cabbage, cauliflower, carrots, radishes, and potatoes. Many local dairy farmers produce vegetables in addition to the crops used in feeding their cattle. The area surrounding Wrenshall is well known for its cabbage production. Before World War II, 150 vegetable producers in the vicinity of Duluth were organized as a market garden association. A fruit growers' association of approximately 500 farmers shipped raspberries to Chicago and New York markets. Although many of these farmers have been attracted to indus-

[4] This section is based largely on an interview with Mr. D. T. Grussendorf, St. Louis County agricultural agent.

tries in Duluth, a decrease in labor demand would cause many to return to their former agricultural enterprises.

The potential raspberry production is very great in this region for three reasons: (1) the lake causes berries to delay ripening until August, by which time they are off the market farther south; (2) there are many areas of well-drained soils; and (3) moisture from dew and fog caused by the lake helps make high quality berries.

In 1944 a large percentage of the rural area in townships north and northwest of Duluth was zoned as restricted land. No new permanent inhabitants may move into these submarginal agricultural districts except for specified non-agricultural activities. In conformity with a state law of 1939 permitting such action, this zoning was carried out by the voters in most of the townships of St. Louis County. As a result, much expensive road maintenance, school expense, and welfare assistance will be eliminated. Many potential farmers will be spared the financial embarrassment of "trying out" a farm in submarginal districts before losing all their savings in a futile attempt to make a living.

CHAPTER III

DESCRIPTION OF THE FORMATIONS

The rocks exposed in and near Duluth belong to relatively few formations, all pre-Cambrian, and mainly Keweenawan in age except the glacial and associated deposits. The thickness of the deposits, however, is tremendous. Some of the estimated thicknesses seem altogether too high to be credible, but they are based on good exposures and have been checked by excellent geologists from time to time. Data have not been found to justify any substantial reduction in estimates of thickness; in fact, detailed work has served to increase these estimates.

Geologic Formations of the Area

AGE	FORMATION	ESTIMATED THICKNESS
Pleistocene (Late Wisconsin)	Glacial Lake Duluth sediments	0–50 (?)
	Glacial deposits of the Superior lobe	0–200+
Upper Keweenawan	Lake Superior series	
	Fond du Lac beds	2000+
Middle Keweenawan	Duluth gabbro and Beaver Bay complex	20,000+
	Keweenaw Point volcanics	20,800±
Lower Keweenawan	Puckwunge formation	200
	Unconformity	
Knife Lake Time (?)	Thomson formation	20,000±
	Unknown	

The Thomson Formation

The oldest rocks exposed in the Duluth area are found south and west of the city, particularly along the St. Louis River and on the upland in and near Carlton and Cloquet. (See Plates 6, 7, 9, and 10.) More or less extensive exposures also occur to the southwest in Carlton and Pine counties as far as the station of Denham on the Soo Line in T. 45 N., R. 21 W.[1]

In the region about Carlton, Thomson, Scanlon, and Cloquet, exposures are abundant, many as typical roches moutonnées in long structurally controlled east-west ridges. The graywackes are more resistant than the slates and consequently form many of these ridges. The south slope is characteristically a dip slope (Figure 6) and the north slope often a joint plane. Joint and fault planes often mark the abrupt ends of the

[1] A detailed description of the formation over its entire area is given in G. M. Schwartz, "Correlation and Metamorphism of the Thomson Formation, Minnesota," *Bulletin of the Geological Society of America,* 53:1001–20 (1942).

ridges. Diabase dikes which trend about N. 30° E. form gaps in the ridges and are believed to follow faults because they offset the ridges.

ROCK FACIES

The Thomson formation consists of interbedded slates, graywacke-slates, and graywackes, varying southwesterly with the progressive metamorphism to phyllite, mica schist, and garnet-mica schist. The latter two

FIGURE 6. — Bedding plane cliff of graywacke; the opposite side is a joint plane. Northern Pacific Railway, just west of the St. Louis River.

facies occur beyond the Duluth area as outlined in this report. Locally graywacke excludes other facies, but between Cloquet and Scanlon slate greatly predominates. Ripple marks occur at a few places, but other primary sedimentary structures are not conspicuous. By and large, however, alternation of the three principal facies is characteristic. An excellent exposure of an 830-foot typical section along the St. Louis River in the gorge below the Thomson Dam shows the following proportions: graywacke 48.5, graywacke-slate 25.2, slate 26.3. Although these proportions cannot be applied to the entire formation, they probably are representative and emphasize the desirability of using the term *formation* instead of slate.

Distribution of Facies. Between Scanlon and the north side of Cloquet, slate beds exclude graywacke for considerable thicknesses. Along the north side of Cloquet, near and in the St. Louis River, massive beds of graywacke predominate. At one place 25 feet of graywacke beds exclude slaty beds. Extensive continuous exposures in the gorge of the St. Louis River below the Thomson Dam are at least 50 per cent graywacke. Carbonate concretions characterize all facies.

Slate. The slate beds of the formation have well-developed slaty or flow cleavage. Thin sections from several of the best exposures show mainly sericite, quartz, carbonate, chlorite, feldspar, leucoxene, epidote, and magnetite. Under high magnifications the well-oriented sericite is conspicuous and constitutes 40 to 50 per cent. Much of the remainder is clastic quartz with occasional clastic feldspar. Large carbonate grains perhaps represent incipient metacrysts. Finest grained specimens contain considerable translucent material, probably kaolinite. Other specimens have more chlorite and epidote and less sericite. Bedding often shows even in hand specimens. Dark irregular carbonaceous streaks are abundant in local beds.

Graywacke. The thickness of graywacke beds ranges from a few inches to many feet. Locally thickness varies greatly within a few feet. Most beds are relatively fine-grained, but in some angular clastic grains can be recognized megascopically. The coarsest graywacke observed occurs in the north bank of the St. Louis River in Sec. 13, T. 49 N., R. 17 W., and has subangular grains up to 3 mm. in diameter. An exposure on Highway 61, 3 miles southwest of Carlton, contains a few siliceous pebbles and concretions.

Many varieties of the graywacke examined in thin section are essentially identical except for grain size. The grains are mainly subangular quartz, but twinned feldspar grains are not uncommon. The groundmass is very fine fragmental quartz with chlorite, sericite, and less commonly leucoxene, talc, limonite, and sphene. Chlorite and sericite are usually oriented. Metacrysts of siderite occur in some beds, enclosing quartz fragments and showing oxidation. Many large fragmental grains are rounded, and recrystallization has developed an internal mosaic. Secondary growth was observed. Unusual softness of some massive graywackes in the field suggests a high carbonate content. However, thin sections show minor carbonate but an abundant chlorite matrix.

Graywacke-slate. A common type interbedded in the Thomson series is intermediate between slate and graywacke. It differs from the typical slates in being obviously more quartzose, more massive, and having less flow cleavage. The beds are not so massive as the typical graywackes and have a definite cleavage which is entirely lacking in some graywackes, although thin sections usually show orientation of the micaceous minerals.

The minerals of the graywacke-slate are quartz, feldspar, chlorite, and sericite, with small amounts of carbonate and leucoxene. There is more chlorite and sericite than in typical graywacke and much very fine fragmental quartz. The quartz content is higher than in the slates, and the clastic grains are somewhat coarser.

Carbonate Concretions. Characteristic of the Thomson formation are the abundant carbonate concretions. They are described in more detail in a separate paper,[2] but a brief summary is given here. They occur throughout the entire formation. Many occur near the tops of beds, but some are scattered in massive beds. They usually occur in zones parallel to the beds and are a valuable guide to the dip and strike. They range from nodules less than an inch in diameter to irregular rounded masses

[2] G. M. Schwartz, "Concretions of the Thomson Formation, Minnesota," *American Journal of Science,* 240: 491–99 (1942).

with a long dimension of fully 3 feet. They are most commonly roughly prolate ellipsoids. Same are elongated and flattened in the plane of the cleavage which passes through them. Most of the concretions are mainly calcium carbonate, but iron carbonate and probably manganese carbonate locally oxidize to a yellow and black residue. The texture varies from coarse radiating aggregates forming concentric shells to a rather dense, fine-grained massive carbonate. Clastic quartz is commonly enclosed in the concretions.

Siliceous-carbonate Lenses in Slate. Thin siliceous-carbonate lenses are characteristic of certain exposures in and near Cloquet that N. H. Winchell referred to in his description of the Carlton area.[3] Their most unusual feature is their resemblance to bedding, but they are oriented with the flow cleavage, and the relation to the bedding is that usually found on the limbs of folds. Thin sections show that carbonate is not abundant and the carbonate grains are embedded in a matrix of mainly fine fragmental quartz. It is not possible to prove orientation of the lenses with the bedding and reorientation during rock flowage, but either this is the case or the lenses represent segregation during development of the slaty cleavage. The fact that the bedding may be traced across the lenses suggests that they represent only a partial rearrangement of original constituents.

Thin sections show predominant clastic quartz grains, but also two carbonates, a clear transparent variety distributed throughout the slide, and another forming clusters or skeletal metacrysts, either siderite or some iron-bearing carbonate now stained with limonite.

A section of another carbonate lens in slate, also from Cloquet, shows abundant euhedral carbonate metacrysts. The matrix consists of quartz and well-oriented sericite. Rocks with similar structure are exposed south of Denham near the granite contact. In these the matrix is a coarse biotite schist.

The Thomson formation, occupying an area west and southwest of the head of Lake Superior and southwest of Duluth, is on the north limb of the Lake Superior syncline. It should be noted on the geologic map (Plate 1) accompanying United States Geological Survey Monograph 52, that the main axis of the Lake Superior syncline does not pass through the head of the lake (Duluth-Superior) but strikes the south shore near Ashland, Wisconsin, and thence trends southwesterly across Wisconsin into Minnesota. This general location of the axis and the evidence for it was emphasized by Thwaites in the results of his work on the south shore of Lake Superior.[4]

A minor axis of the synclinal folding passes south of Duluth and Superior, but the nearest outcrops of Thomson formation are fully 10 miles

[3] N. H. Winchell, *The Geology of Minnesota,* 4:559 (1899).

[4] *Sandstones of the Wisconsin Coast of Lake Superior* (Wisconsin Geological and Natural History Survey Bulletin 25, 1912), p. 88.

to the northwest of even this minor axis. The complex folding of the Thomson formation is clearly not a result of the deformation that resulted in the Lake Superior syncline, but is rather the result of one of the older periods of folding that affected the rocks of the Lake Superior region and the pre-Cambrian shield in general. The lower and middle Keweenawan rocks involved in the synclinal folding lie unconformably at gentle angles on the complexly folded Thomson slate. An exposure in the bed of the St. Louis River (described by G. M. Schwartz, *op. cit.,* p. 1008) shows the unconformity with a quartz pebble conglomerate lying on slate. The conglomerate strikes N. 60° E. and dips 7° SE., whereas the slate strikes N. 70° E. and dips 45° S. The slaty cleavage strikes N. 88° E. and dips 50° N.

About 6 miles northeast of the conglomerate just described and 2 miles west of the Duluth city limits is a good series of exposures in Secs. 17 and 20, T. 49 N., R. 15 W. One fourth mile east of the northwest corner of Sec. 20, Thomson beds, Puckwunge conglomerate and sandstone, and Middle Keweenawan lava flows are all exposed within a distance of 350 feet of each other. The Thomson beds strike N. 85° E. and dip 84° S., whereas the Puckwunge beds above strike N. 10° W. and dip 15° E. The pronounced structural discordance of the two formations is evident wherever they are exposed near each other. The overlying flow has an attitude similar to that of the Puckwunge and this fits into the regional Lake Superior structure, but the Thomson beds clearly owe their structure to an earlier deformation.

There is abundant evidence of a gentle deformation later than the main period of development of the slaty cleavage of Thomson formation. It is entirely possible that this later gentle deformation is related to the deformation of the Lake Superior syncline. The 7° to 15° dips of the basal Keweenawan conglomerate represent about the prevalent angle of the dip of Keweenawan and Animikie rocks for the Minnesota coast of Lake Superior from Duluth to Pigeon Point.[5] The deformation and slaty cleavage found in the Thomson formation below the unconformity clearly preceded the formation of the Superior syncline, as it now exists, and represent about the same degree of deformation and metamorphism as the Knife Lake slates of the Vermilion district.[6]

FOLDS

The exposures of the Thomson formation show abundant evidence of folding, but complete folds are revealed only locally and these are mainly minor folds, at least of the second order (Figures 6 to 9). When detailed mapping was started, it was expected that the regional structure of the area could be worked out by the application of the principles of the relation

[5] See, for example, details presented in Minnesota Geological Survey Bulletins 24 and 28.

[6] J. W. Gruner, "Structural Geology of the Knife Lake Area of Northeastern Minnesota," *Bulletin of the Geological Society of America,* 52:1577–1642 (1941).

of minor to major structures. This expectation was only partially realized. Deterring factors are lack of outcrops in critical areas, and even more serious, the lack of recognizable horizons in the formation. Minor structures give a fairly accurate picture of the kind of folding and of the general location of major and minor axes, but without key beds to trace the outline and determine repetitions, any regional structure that may be inferred is bound to be but one of several possibilities.

The prevalent strike of the beds in exposures throughout the main area of outcrop of the Thomson beds is nearly east-west. The same is true of the cleavage; its strike generally varies only slightly from that of the beds, but its dip is generally much steeper. The prevalent east-west strike of slaty cleavage and bedding shows that the major folds strike east-west in contrast to the northeast-southwest strike of the Animikie and Keweenawan beds and fold axes of northeastern Minnesota.

Where the strike of the beds and cleavage is nearly parallel, erosion has resulted in many long narrow ridges. These are conspicuous on aerial photographs and furnish a good check on the prevalence of east-west strikes of the beds. Where the strike of the cleavage is at an angle to the beds of slate, ridges do not continue far; erosion along the cleavage seems to have destroyed their continuity. The general elongate shape and rounded profile of the ridges suggest the possibility of their being folds, but actually this is rarely the case. They are mostly rounded resistant beds.

The dip of the beds is generally moderate. The average of 225 south dips is 53° and of 80 north dips 57°. The moderate dip and the slight difference between the north and south dips indicate that the major folds are of an open type and nearly symmetrical. This is also indicated by rather low, open, minor folds. Tabulation of 544 well-distributed dip observations, with general east-west strikes over the area of outcrop, shows that 71 per cent are to the south. Averages along strips both north and south and east and west gave about the same percentages as those given for the entire area. At places, as along the St. Louis River, exposures are continuous enough to eliminate the danger of missing north dips. Dips to the east or to the west are comparatively few. The results of this tabulation agree with the field impressions. This prevalence of south dips was noted long ago by N. H. Winchell.

The pitch of folds in the Thomson beds is shown especially well by the trace of the bedding on weathered surfaces of the slaty cleavage. The pitch of the bedding shows up plainly (Figure 7) and is easily read; the consistency of the readings suggests that the observations are particularly dependable. The pitch of drag folds coincides with the general pitch of major folds and was used where the trace of the bedding was not visible. The fact that most major folds pitch gently eastward is brought out graphically by the plotting of pitch observations. This shows that the majority of folds pitch east between 10° and 30°. The eastward pitch was no doubt increased about 10° by the late Keweenawan sinking of the Superior syncline.

Inasmuch as the strike of the beds is normally about east-west, the axial planes are oriented in that direction; nearly symmetrical minor folds and equal dips on the limbs indicate that the axial planes are nearly vertical and pitch east as shown above. The beds to the west are thus generally beneath those of the east. The gentle pitch of the folds results

FIGURE 7. — Trace of bedding dipping about 40° to the east (right) on cleavage plane in slate indicating an eastward pitching fold. West of Northwest Paper Company plant, Cloquet.

in many outcrops gradually plunging beneath the drift, in the direction of pitch. This is true, not only of anticlinal exposures, but also of the resistant beds on the limbs of folds or in regions of monoclinal dips.

A summary of known facts and inferences regarding the folds of the area serves to clarify the situation:

Facts

1. The strike of the beds is mainly east-west.
2. The dip of the beds is south and north in the ratio of 71 to 29. The dips average about 55°.
3. The strike of the flow-cleavage is also generally east-west.
4. The dip of the cleavage is almost invariably steeper than that of the beds.
5. The pitch of the folds is low and mainly to the east, but west pitches also occur.
6. Minor folds are often broad and open; others are only mildly asymmetrical.

Inferences

1. The axes of the major folds strike generally east-west.
2. The major folds are of a rather open, nearly symmetrical type, and isoclinal and overturned folds are generally absent as shown by the fact that the cleavage always dips steeper than the bedding.

3. The axial planes of the major folds are nearly vertical.
4. The thickness of the beds represented by the outcrops is great because of the generally east-west strike of the beds and predominant south dips.

Dips and strikes of bedding and cleavage were plotted for the area of principal outcrop on a scale of four inches to the mile. Anticlinal and synclinal axes were then sketched in wherever suggested by the dip of the bedding. In general it was found that minor axes with trends varying not over 15° from east-west were fairly common, but as a rule it was impossible to extend these axes for any great distance. Few could be mapped over a length of a mile with any degree of confidence. Lack of outcrops often prevented extension, but in areas of abundant exposures projection of axes was prevented by observations indicating only monoclinal dips.

A few exceptions to the above general statements deserve mention. In the south half of Secs. 7 and 8, T. 48 N., R. 16 W., a well defined syncline trends N. 84° E. for nearly 2 miles. Uniform southerly dips seem to preclude its extension eastward beyond the east line of Sec. 8. Lack of outcrops to the west leaves its extension westward an open question.

In the south half of Secs. 31 and 32, T. 49 N., R. 16 W., an anticline extends across both sections near the south line. In Sec. 32 the axis trends east-west. In Sec. 31 the trend is S. 83° E. The axis extends into Sec. 36 of the adjacent township where it may swing sharply northwest and connect with an anticlinal axis southeast of the center of the section. To the north of this anticlinal axis from one fourth to three eighths of a mile is a nearly parallel synclinal axis of about the same length. Lack of outcrops at each end leaves open the possibility that this axis extends considerably farther.

A few folds were noted on aerial photographs, available for the area along the St. Louis River through the courtesy of the Minnesota Power and Light Company. North of the Thomson reservoir, in the northeast portion of Sec. 5, T. 48 N., R. 16 W., a distinct syncline is indicated on the photograph. Massive graywacke beds form dip slopes that show the curve of the bed. The pitch is to the east and older beds successively appear along the axis, from east to west. The pitch is 15° E. and the dip on the limbs varies from 15° to 78°, but most are near 35°. A small sharp anticlinal axis exists on the south side but is only partially exposed.

Many minor folds were observed. These need not be described in detail but characteristic examples will be mentioned. Small folds a few feet, or at most a few tens of feet across, were observed in the better exposures (Figure 8). Some are broad, open, symmetrical folds in the more massive beds, such as those beneath the bridge over the St. Louis River in Jay Cooke Park. In the slaty beds, the folds are more likely to be somewhat asymmetrical, doubtless a result of differential movement on the limb of

FIGURE 8. — Flat anticline of slate pitching gently eastward, forming an anticlinal ridge. St. Louis River.

a large fold. A good example occurs in a Great Northern railway cut about 1000 feet north of Highway 61, at the west edge of Carlton. Along the St. Louis River, where exposures are particularly good, very flat, gently pitching open folds were observed. In the reservoirs above the dams, the anticlinal ridges form well-defined reefs projecting out into the river. A good example may also be seen just below the Scanlon Dam.

Much more minute folding, often measured in inches, is common and presents considerable variety. Some of these gentle, wavy, small folds resemble ripple marks on the bedding planes, and only by examining the cross-sections of the rocks affected can they be distinguished. The criterion used is that in folding the rock must show the structure in successive layers in cross-section. Ripple marks show only the single apparent fold at the bedding plane. The minute folds naturally occur in the slaty beds that were relatively incompetent. An extreme example was noted in a Northern Pacific railway cut southeast of Carlton (NW¼, SW¼, Sec. 8, T. 48 N., R. 6 W.). Here the bedding plane has a fluted appearance as a result of folding, with the distance from crest to crest

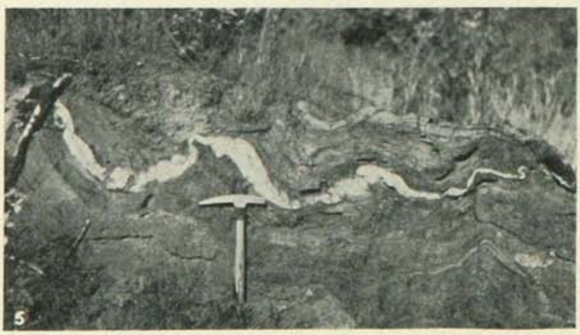

FIGURE 9. — Vein quartz formed along minor folds in phyllite. Just west of Atkinson, Carlton County.

only an inch or two. In cross-section the folds are asymmetrical, indicating the relative shear of the beds. Quartz veins commonly follow minor folds and emphasize them (Figure 9). Some of the more complex vein quartz folds resemble ptygmatic folds as, for example, in Sec. 8, T. 48 N., R. 16 W., southeast of Carlton. Many other examples were noted. Some of the quartz folds are asymmetrical, indicating differential movement in beds, but most are symmetrical or irregular.

SLATY CLEAVAGE

In the vicinity of Carlton and Cloquet, where exposures are most extensive, the slaty cleavage is highly developed and affords diagrammatic relations between flow cleavage, bedding, fracture cleavage, and minor

FIGURE 10. — Slate beds dipping south with nearly vertical flow and fracture cleavage, the latter emphasized by weathering. Recreation field, Carlton.

folds (Figures 6 to 12). The highly argillaceous beds have excellent slaty cleavage. Argillaceous material mixed with sandy material has formed graywacke-slates that show cleavage from well-cleaved slates to almost massive beds with poorly developed cleavage. Massive graywacke beds with jointing and fracturing are abundant throughout most of the formation. Cleavage is lacking in many of these massive competent beds, but thin sections show that sericite and other elongate or platy minerals are commonly oriented.

A great variety of relations was observed between the slaty cleavage and the bedding. In general, however, the angle between the two is relatively large, indicating, along with other evidence, that the major folds are of a relatively open type. The pitch is commonly indicated by the trace of the bedding on the cleavage planes (Figure 7).

At places, the flow cleavage, and bedding planes appear to coincide or are so closely parallel that any divergence is not easily detected. In general, thin slate beds show an acute angle between bedding and cleavage.

As previously noted, the average dip of the beds in the main area of outcrop is about 55°. The cleavage is always steeper than the bedding except where the two are parallel. Tabulation of 100 south-dipping cleavage planes gave an average dip of 73°, whereas 48 north dips averaged 78°. In addition, there were several vertical dips excluded from the tabulation. These observations were made in the main area of outcrop between Atkinson and Cloquet. The steeply dipping cleavage is important in connection with inferences as to the general structure and estimates of thickness of the beds comprising the Thomson formation. It indicates that overturned folds are absent and isoclinal folds are possible only where cleavage and bedding are parallel.

Inasmuch as the most common dip of the beds is to the south, the dip of the slaty cleavage is generally either nearly vertical, or steeply south, with a nearly east-west strike. This relation is, in a large measure, the result of shearing concentrated in the slate beds between massive graywacke beds, thus aiding in the development of the slaty cleavage.

The cleavage, which is well developed in the slate, was in places also observed to extend into the graywacke beds for an inch or two. Where the cleavage extends into the graywacke-slate or graywacke, it generally shows a sharp change in angle, having been less affected by the rotation due to shear. The cleavage may be absent from the graywacke, and instead there are joints probably formed by the same shearing stress (Figure 13).

The divergence of the dip of the cleavage in graywacke and in slate may amount to many degrees. In the channels of the St. Louis River, along the north side of Cloquet, there is an extreme example of divergence: the beds of graywacke-slate and slate both dip 60° S.; the cleavage in the slate dips 83° S. and that in the graywacke dips 60° N., a divergence of 37°. Divergences between 10° and 20° are common.

It was noted that the cleavage planes are generally approximately parallel to the axial planes of minor folds. In these examples it is evident that the cleavage is independent of the bedding.

FRACTURE CLEAVAGE

The detailed work that has been done on the formation indicates strongly that the extreme development of fracture cleavage is partly a result of a later period of mild deformation that affected the formation, perhaps long after the development of the flow cleavage. Evidence of this later deformation includes faulting, minor shear zones, folding of cleavage, and fracture cleavage. There are many examples of cleavage blocks that were folded with apparent simultaneous development of fracture cleavage.

Figure 11 represents a common type of fracture cleavage block. The flow cleavage is shown as horizontal with the bedding dipping to the right. Both end and side faces are fracture cleavage surfaces of a somewhat rhombic block. Rhombic blocks of many sizes are common and in

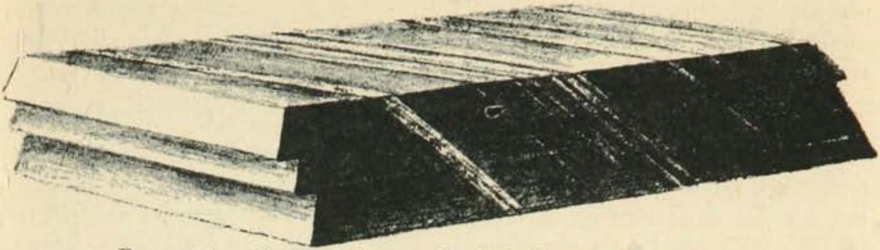

FIGURE 11. — Sketch of cleavage block of Thomson slate, Carlton.

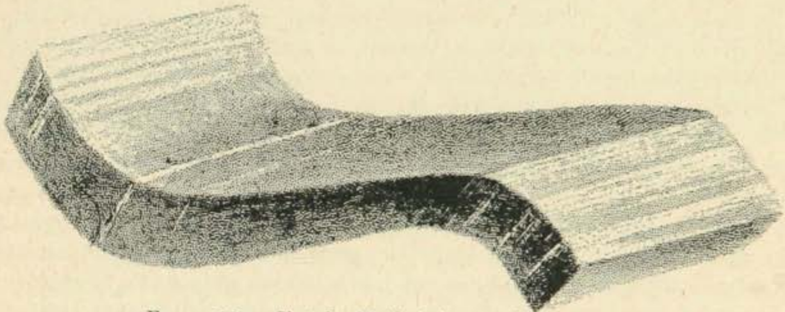

FIGURE 12. — Sketch of folded cleavage block of slate.

fact make up large parts of some slaty outcrops. Blocks of this type are well shown in exposures just south of the Northern Pacific railway station in Carlton.

Washboard-like surfaces in places result from fracture cleavage at an angle to slaty cleavage. A joint face in a railroad cut furnished a cross-section of such an example.

The curving of fracture cleavage planes where formed by differential movement between beds has been emphasized in many examples described by other writers. Curving seems to be the exception rather than the rule in the fracture cleavage in the Thomson beds, although good examples were observed. S-shaped curving is frequently found in slaty cleavage of thin slate beds between competent graywacke beds. In some cases the S-shaped cleavage suggests a deformation after the development of the flow cleavage, perhaps during the later mild deformation that affected the region.

Many outcrops show closely spaced fractures parallel to the flow cleavage, which are emphasized by weathering. Examination of many examples of this kind suggests to the writer that this is in reality a variety of fracture cleavage developed along certain flow cleavage planes. The question naturally arises as to why these should be referred to as fracture cleavage. The answer is that they are actually fractures but they are spaced a visible distance apart, whereas flow cleavage planes are almost infinitely closely spaced. That is, fracture planes formed only along certain of the slaty cleavage planes where these were subject to later shearing between more competent beds.

JOINTS

The Thomson formation is characterized by extensive jointing. Most large exposures show not only several planes of jointing forming sets and systems but also jointing of several distinct sizes in the same rocks. The smaller joint planes are closely spaced and grade into fracture cleavage. The larger joints are very well defined and may be traced for hundreds of feet in exceptional cases.

The joints have rather consistent orientation in parallel sets in individual outcrops, and some sets seem to be repeated over wide areas, but there is too much variation to work out more than general sets.

The dips and strikes of a large number of joints were determined. By far the greater number strike within 40° of north and south. The dips are mostly steeper than 45°. There is a noticeable concentration of strikes at about N. 30° E. and of dips from vertical to 60° W. It is noteworthy that most of the joints are either cross or transverse with respect to the strike of the beds and of the slaty cleavage—normal to the linear structure on axes of folds. In the case of joints which may have been formed by later deformation, the stresses were not necessarily such that only cross or transverse joints were formed. Rather bedding planes and flow cleavage planes relieved stresses in their direction and thus in reality played the role of joints in relieving the stress. It probably would lead to erroneous conclusions to work out any system of stress based purely on the joints in this area.

In general, the massive graywacke beds are cut by rather large continuous joints that are widely spaced (Figure 13). Commonly minor and less regular joints occur between the master joints. Only the master joints were considered important in the regional structure. Many slate beds are cut by a series of smaller joints, giving a blocky aspect to the exposures. In these, the flow cleavage planes always play the role of joints. As a rule, the bedding is unimportant.

FAULTS

Recognizable faults are not common in the Thomson area, but the lack of good horizon markers makes it possible that small faults escape discovery and the large amount of covered area makes it certain that many zones of shearing might be masked by surficial deposits. In spite of these handicaps, however, certain faults have been mapped. The faults fall into a natural classification as major and minor faults. The major faults were recognized mainly by the aid of aerial photographs in the region of numerous outcrops along the St. Louis River. These show that prominent strike ridges end abruptly and at places appear to be offset.

FIGURE 13. — Joints intersecting a bedding plane of graywacke. St. Louis River valley, Jay Cooke State Park.

The lack of definitely recognizable horizons, however, precludes the correlation of apparently offset ridges, at least with certainty. These faults are parallel to zones along which there are many diabase dikes. The diabase is more easily weathered than the slate and graywacke, and accordingly a depression or gap occurs where the faults and dikes cut the ridges. It is believed that the dikes were intruded along pre-existing faults that formed a well-defined series striking approximately N. 30° E. Not all of the gaps in the ridges are occupied by diabase dikes, for one of the most prominent gaps in the abundant exposures southeast of Carlton appeared to be simply a shear zone, and slate and graywacke beds could be traced practically across it.

Opposite the plant of the Northwest Paper Company in Cloquet, a heavily brecciated zone crops out on an islet in the river, about 20 by 30 feet across, with other masses along the east bank and in the water. The fault zone also shows at the bend in the river a few hundred feet to the north. It is probable that the course of the river there is largely determined by the fault, which has a generally north-south trend.

The minor faults are of various types. Relatively thin graywacke beds occur in a thicker slate series and the graywacke adjusted itself during deformation by minor step faulting.

Intersecting faults occur just beneath the highway bridge over the St. Louis River near the west entrance to Jay Cooke Park (Plate 6). A fault with low dip shows only a small offset in the beds, but the intersecting steeper fault has a wide divergence in strike of the beds on the two sides.

Well-defined slickensided surfaces were observed at a few places, but further detail is lacking because of the cover of glacial drift.

DEFORMATION SUBSEQUENT TO THE MAIN DEFORMATION

A later, mild, deformation has been referred to above at several places. A short summary of some of the evidences and results of this deformation is in order.

Folding. One of the most obvious, as well as conclusive, evidences of later deformation is the folding of the flow cleavage planes (Figure 12).

An extreme example was noted in the channel of the St. Louis River in the SE¼ of Sec. 10, T. 48 N., R. 16 W., where the cleavage planes have been contorted into a series of irregular folds. A diabase intrusive nearby may have had much to do with this structure.

Near the east quarter corner of Sec. 20, T. 48 N., R. 17 W., cleavage slabs are sharply folded in asymmetrical folds which pitch at an angle of 30° in a direction N. 75° E. Folded cleavage is commonly best seen on a cross-joint surface where the trace of the cleavage is etched out by weathering. On a cliff facing a swamp in the SE¼ NW¼, Sec. 19, T. 49 N., R. 16 W., a horizontal rock surface shows minutely folded cleavage forming an irregular structure. That such folding was developed much later than the cleavage seems evident. Along the east side of the St. Louis River similar structure was noted by Winchell.

Below the Northern Pacific railway bridge over the St. Louis at Thomson, slickenside surfaces were noted cutting across the slaty cleavage at an acute angle.

Along the south bank of the St. Louis River in the SW¼, Sec. 9, T. 48 N., R. 16 W., the beds have unusually low dips and the slaty cleavage likewise has a dip of only 20°. The cleavage is curved and a series of folds pitch gently to the east. It seems probable that the abnormally low dip of both bedding and cleavage is a result of secondary folding.

Shear or Fracture Cleavage Zones. Many well-defined narrow zones of shearing cross the other structures in the slate and form narrow zones of fracture cleavage or offset the slaty cleavage. This shows only faintly on photographs, but such shear zones were observed to extend nearly horizontally across a joint face in a quarry in Thomson village; the bedding dips 58° S. and the cleavage 85° S., whereas the later shear, which affects the flow cleavage particularly, dips roughly 5° S. In many cases this seems to be a shear or offset in the flow cleavage, which opened the cleavage planes, but probably developed few new fracture planes. It is thus a fracture cleavage developed from slaty cleavage by shear concentrated in a narrow zone, commonly from 1 to 3 inches wide.

THICKNESS

Although detailed structure of the Thomson slate cannot be worked out, available data on thickness suggest some limits.

The formation is known to exist over an area 40 miles east and west and 25 miles north and south, throughout which east-west strikes of fold axes, beds, and cleavage are noteworthy. Winchell noted that prevailing dips are to the south. Tabulation of 544 dip observations by the writer shows that 71 per cent are generally to the south. North dips average 57° and south dips 53°. Dips to the east or west are negligible. Graphic solution of the problem of the effect of the folding on thickness shows that 42 per cent of the distance across the strike with allowance for dip gives an apparent thickness of 45,000 feet of beds on a north-south extent of 25 miles. Allowing a 50 per cent reduction for flat dips on the axes of anticlines and synclines as well as undiscovered causes of duplication gives a minimum figure of more than 20,000 feet. Data which would reduce this figure have not been found.

CONTACT METAMORPHISM BY THE DULUTH GABBRO

As previously noted the Thomson formation is exposed close to the Duluth gabbro contact in Sec. 20, T. 49 N., R. 15 W. (Plate 8). A number of outcrops occur along the Midway River from a point west of the center of the section to the northeast corner. Along the east line are a few exposures of metamorphosed flows, but a short distance east of the northeast corner gabbro is exposed. All the slate exposures show metamorphism with the development of hornfels. The cleavage is largely destroyed, and conchoidal fracture is characteristic.

In thin section, slate collected near the center of the section is spotted. The groundmass is largely fine-grained biotite. The spots are incipient metacrysts of cordierite.

The graywacke is less affected than the slate. The matrix has largely recrystallized to biotite, but coarser fragmental quartz and feldspar grains are essentially unaffected. In more metamorphosed specimens feldspar forms a matrix for quartz, indicating recrystallization. The texture is decidedly granoblastic.

Other specimens were collected in the NW¼ of Sec. 20, T. 49 N., R. 15 W., about 2000 feet horizontally from the contact of gabbro, but these show obvious baking. The slaty facies shows faint spotting under polarized light; biotite has formed at the expense of chlorite, and magnetite is abnormally abundant. The graywacke is especially high in dusty magnetite; biotite and sericite form the matrix. In the normal graywackes, chlorite is common, but biotite is never present so far as known.

DIABASE INTRUSIVES

Throughout much of the area of the Thomson formation, but particularly in the Carlton-Cloquet region, dikes, less commonly irregular intrusions, and a few sill-like bodies of diabase cut the slate. Petrographically these are practically identical with the Keweenawan extrusives of the north shore of Lake Superior. The dikes are more easily weathered than the slates and graywackes and often form gaps in the ridges. Aerial photographs suggest the continuity of the dikes for long distances striking N. 39° E. Offsets in ridges further suggest that some dikes occupy fault zones.

The slates and graywackes locally show slight baking near the contacts and, where the dikes are large and closely spaced, have formed fairly well-developed hornfels. Irregular intrusives well-exposed at places in the bed of the St. Louis River below the Thomson Dam deform the structure. Locally more severe contact effects were noted. A reddish graywacke near a dike in the river bed shows secondary feldspar. Dusty hematite occurs around the periphery, and sericite is abundant within the feldspar grains. Quartz areas are granoblastic. The effect recalls that at Pigeon Point, where a large sill intrudes quartzites.

CORRELATION OF THE THOMSON FORMATION

The series of slates exposed in the Carlton-Cloquet area have been frequently referred to in discussions of Lake Superior correlation problems, but only Spurr (1894), Winchell (1899), and Harder and Johnston (1918) have presented any details on the Thomson formation. None of these investigations undertook anything like a complete mapping of the formation. A review of all opinions which have been expressed on this correlation would take much space, and accordingly only a tabular statement of previous correlations will be given.

AUTHOR	DATE	CORRELATION
Irving	1883	Animikie
Winchell, N. H.	1890	Animikie and Taconic (2 series)
Spurr	1894	Keewatin (Lower Huronian)
Winchell	1898	Animikie and Keewatin (Lower Huronian) (2 series)
Leith	1903	Lower Huronian
Leith and Van Hise	1911	Animikie
Harder and Johnston	1918	Animikie (possibly Lower Huronian)
Leith, Lund, and Leith	1935	Upper Huronian (Animikie)

Most of these correlations were made either as suggestions on broad general grounds, or they were based purely on lithology. None were made with all the facts now available, and it is believed that a consideration of all the facts leads to a more definite conclusion, although it may be that exact correlation will never be possible because of the large covered areas.

Facts which must be taken into account include the following:

1. The Thomson formation differs lithologically from the Animikie sedimentary rocks of the Lake Superior district.

2. The Thomson formation is highly folded and metamorphosed, so that the lowest grade has excellent slaty cleavage. In this respect it resembles the Knife Lake series of the Vermilion district and not the Animikie Virginia slate.

3. The strike of the beds, cleavage, and axial planes of the folds is

predominantly east-west. This is at an angle of about 35° to the prevailing regional structure of younger beds related to the north limb of the Lake Superior syncline. At Duluth the two structures strike at about right angles to each other.

4. The Thomson formation is separated from the Lower Keweenawan by a pronounced angular unconformity.

5. The Keweenawan rocks overlying the Thomson partake of the same regional structure as the Animikie beds of the north shore of Lake Superior—that is, a strike generally northeast and a dip of 10° SE. A pronounced structural discordance, therefore, exists between Animikie-Keweenawan beds and the beds of the Thomson formation. No structural discordance is known between Animikie and Lower Keeweenawan beds in Minnesota, but a disconformity evidently exists in the Grand Portage region.

6. The Thomson has suffered progressive regional metamorphism with low-grade rocks in the Carlton-Cloquet area and high-grade metamorphics to the south near the granite contact.

7. The granites of central Minnesota have recently been tentatively correlated on the basis of accessory-mineral studies, with granites of Algoman age. Seven additional samples of granites, collected in 1941 from scattered points from Little Falls to Denham, all show accessory minerals characteristic of Algoman granites. The only batholithic Minnesota granite which shows Keweenawan characteristics is the red granite of the Milaca and St. Cloud areas far to the south.

These facts leads to certain interpretations: the Thomson formation of Carlton and Pine counties is pre-Animikie in age and should not be correlated with the Virginia slate for three reasons. First, the structure of the Thomson formation is discordant with the regional Lake Superior synclinal structure as developed in late Keweenawan time. (The Animikie and Keweenawan are in practical structural accordance in northeastern Minnesota.) Second, the Thomson and Virginia formations differ in the nature of the original sediments and in metamorphism. Third, the Thomson formation is greatly metamorphosed in the southern part of its extent by granites which are correlated with the Algoman granite on the basis of accessory minerals and general correspondence of other characteristics; the Thomson is therefore older than Algoman, whereas the Animikie rocks are younger.

As to the correlation of the Thomson formation with other pre-Animikie rocks, there is little direct evidence. On the basis of lithology, metamorphism, and deformation, the formation compares well with some of the Knife Lake series, and reference to the recent summary of Lake Superior correlations [7] leaves no other logical choice. This is not a new

[7] C. K. Leith, R. J. Lund, and A. Leith, *Pre-Cambrian Rocks of the Lake Superior Region* (United States Geological Survey Professional Paper 184, 1935), p. 10.

choice but was suggested by Spurr (1894), Leith (1903), and others. The difficulty is that the position of the Knife Lake series in the lower pre-Cambrian is somewhat doubtful, and the series is complicated in itself (Gruner, 1941).

In any event the Thomson formation is Lower Huronian or older. Its character and metamorphism correspond well with what might be expected in a Lower Huronian formation. The possibility of the Thomson formation and Knife Lake series being the equivalent of formations classified as Archean in Canada is not excluded.

THE PUCKWUNGE FORMATION

The term *Puckwunge conglomerate* was introduced by Winchell[8] and was first applied to exposures in the valley of Puckwunge Creek (now called Stump River) in eastern Cook County. Later Winchell extended the term to cover basal Keweenawan sediments in Carlton and St. Louis counties mainly along the St. Louis River valley just west of Duluth (Plates 6 and 8).

The Puckwunge as it occurs in the Duluth area consists of a little conglomerate at its base that grades quickly into a gray sandstone.

The formation may be seen[9] to lie directly on the Thomson slate only in the bed of the St. Louis River in Sec. 15, T. 48 N., R. 16 W. A good exposure of conglomerate very close to slate occurs along a small creek near the St. Louis River in Sec. 1, T. 48 N., R. 16 W. The largest exposures of Puckwunge in the Duluth area are along a west-facing bluff in Secs. 17 and 20, T. 49 N., R. 15 W. Here the sandstone is bluff, cross-bedded with fairly well-rounded grains. There is a pronounced unconformity between the slate and sandstone. The sandstone is overlain by the lowest flow of the Middle Keweenawan series. Within a foot of the flow, the sandstone looks silicified and, at places, is banded dark and light. The thickness of the conglomerate and sandstone does not exceed 100 feet. Details on this occurrence are given in the township description.

There is some confusion regarding the relations of the Puckwunge to the lava flows because a record of a well at Short Line Park in Sec. 33, T. 40, R. 15 W., given by Winchell,[10] indicates that at the well lava flows lie directly on the Thomson slate (see page 123 for the well log), and the sandstone and conglomerate corresponding to the Puckwunge is interbedded with the lava flows. Unless the samples were not carefully taken, no alternative seems possible. This suggests that the Lower Keweenawan may not be separable from the Middle Keweenawan as the terms are now used.

[8] N. H. Winchell, "New Features of the Geology of Minnesota," *American Geologist*, 20:41–51 (1897).

[9] G. M. Schwartz, "Correlation and Metamorphism of the Thomson Formation, Minnesota," *Bulletin of the Geological Society of America*, Vol. 53, Pl. 1 (1942).

[10] N. H. Winchell, *The Duluth Deep Well* (Minnesota Geological and Natural History Survey Bulletin 5, 1889), p. 31; *The Geology of Minnesota*, 4:567 (1899).

Keweenaw Point Volcanics

BY A. E. SANDBERG AND G. M. SCHWARTZ

A considerable portion of the Duluth area is underlain by a series of lava flows and lesser fragmental rocks which are correlated with the great series of similar rocks on Keweenaw Point, Michigan. The base of this series is exposed at the southeast edge of Duluth, particularly in Secs. 17 and 20 of T. 49 N., R. 15 W., where the lava flows rest directly on Puckwunge sandstone (Plate 8).

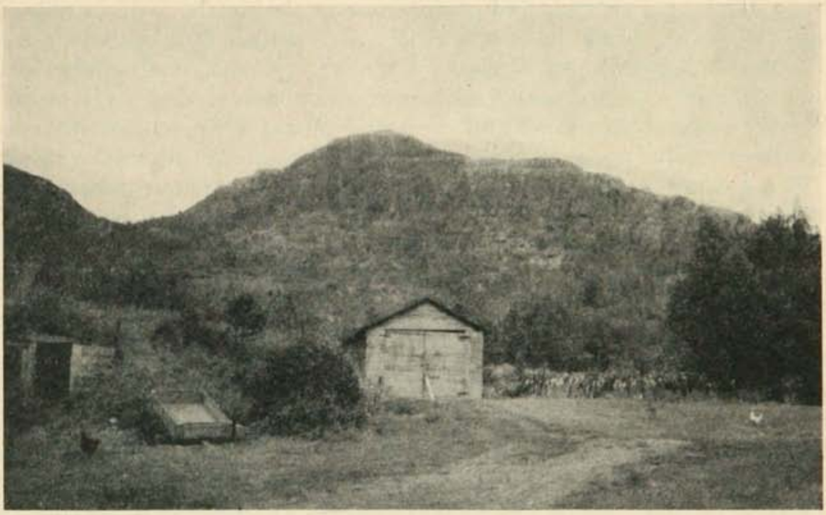

FIGURE 14. — Ely's Peak. Typical of the rocky hills along the Duluth escarpment. The rocks are lava flows.

In 1938 A. E. Sandberg [11] published the results of a very careful study and measurement of the flows and intrusives from the base of the Keweenawan along the shore of Lake Superior to Two Harbors (Plates 1 to 3). This section was checked jointly before its original publication and much of it is repeated here in almost its original form. For this reason Dr. Sandberg should be considered as co-author.

SECTIONS FROM THE BASE OF THE KEWEENAWAN TO TWO HARBORS

The line of the traverse along which measurements were made, begins in the Carlton slate area north of Fond du Lac. It extends northeastward through Short Line Park, into the Duluth gabbro. For this portion it was not possible to work out continuous detail, flow by flow, because of ruggedness of topography (Figure 14) and discontinuity of exposure. The Keweenawan sandstone and flows, stratigraphically below the gabbro,

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

wedge out to the north. About seven flow contacts can be distinguished in the series stratigraphically below the gabbro, though a thickness of 2500 feet suggests that a greater number occur. The gabbro itself comprises nearly 10 miles of the linear traverse.

From Minnesota Point, not far from the top of the Duluth gabbro, to Two Harbors, a distance of more than 25 miles, it was possible to develop an almost continuous flow-by-flow sequence along the beach. This is presented in Plates 1, 2 and 3, which consist of a series of strip maps (A-B to J-K) that fit together into one continuous shoreline strip. The traverse, by Brunton compass and pacing, was plotted in the field on railroad maps on a scale of 400 feet to the inch. As a mantle of lake clays generally extends to within a few yards of the water's edge, contacts between flows cannot be traced inland with continuity; hence, they were plotted as strike lines at lake level and projected inland a convenient distance. Dip observations are generalized. Broken lines signify inferred contacts.

The accompanying table shows the bed-by-bed sequence measured in stratigraphic order. The calculated thickness of each bed is shown, with subtotals carried forward. Sandstone stringers in the tops of flows contribute no thickness to the column but are listed as part of the geologic record. The rock types are discussed later.

The traverse does not include the entire Keweenawan section exposed. Younger and stratigraphically higher beds occur northeast of Two Harbors, but here the angle between the shoreline and the strike of the beds becomes so low that the strike line is scalloped by bays and points. This makes it necessary to correlate outcrops across bays and points, as at Two Harbors (Plate 3, J-K). Moreover, intrusive bodies are probably not so simple as those within the section studied. Detailed work reaches the topmost exposed flow at Two Islands near the Lake-Cook county line before starting down in the section toward the basal Keweenawan at Grand Portage Bay.

DISTRIBUTION OF BEDS

Map		Rock	Thickness (Feet)	Subtotal (Feet)
Pl. 3	J-K	Melaphyre	88	88
"	"	Sandstone (thin)	...	...
"	"	Melaphyre	87	175
"	"	"	67	242
"	"	"	95	337
"	"	Sandstone stringers	...	...
"	"	Melaphyre	90	427
"	"	"	85	512
"	"	Sandstone stringers	...	...
"	"	Melaphyre	48	560
"	"	"	66	626
"	"	"	88	714
"	"	"	17	731
"	"	Series of flows (covered)	294	1,025
"	"	Ophite	50	1,075

Map		Rock	Thickness (Feet)	Subtotal (Feet)
"	J-K, I-J	"	120	1,195
"	I-J	"	33	1,228
"	"	"	31	1,259
"	"	"	33	1,292
"	"	"	140	1,432
"	"	"	108	1,540
"	"	"	97	1,637
"	"	"	30	1,667
"	"	"	22	1,689
"	"	"	26	1,715
"	"	"	135	1,850
"	"	"	67	1,917
"	H-I	"	128	2,045
"	"	"	53	2,098
"	"	"	72	2,170
"	"	"	86	2,256
"	"	"	91	2,347
"	"	"	38	2,385
"	"	"	125	2,510
"	"	"	33	2,543
"	"	"	62	2,605
"	"	"	35	2,640
"	"	" (same as flow to NE)	...	...
Pl. 2	H-I, G-H	Diabase intrusive (ophite inclusions)	1,598	4,238
"	G-H	Ophite	207	4,445
"	"	"	207	4,652
"	G-H, F-G	Series of ophites and melaphyres (under clay banks)	1,444	6,096
"	F-G	Ophite	75	6,171
"	"	Melaphyre	61	6,232
"	"	Ophite	46	6,278
"	"	"	210	6,488
"	"	Sandstone stringers	...	...
"	"	Ophite	49	6,537
"	"	"	20	6,557
"	"	"	74	6,631
"	"	Series of melaphyres and ophites (covered)	1,308	7,939
"	"	Melaphyre	15	7,954
"	"	"	118	8,072
"	E-F	Ophite	181	8,253
"	"	"	237	8,490
"	"	Sandstone	3	8,493
"	"	Ophite	195	8,688
"	"	"	106	8,794
"	"	Sandstone stringers	...	...
"	"	Ophite	20	8,814
"	"	Sandstone stringers	...	...
"	"	Ophite	222	9,036
"	"	Sandstone stringers	...	...
"	"	Ophite	15	9,051
"	"	Sandstone stringers	...	...
"	"	Ophite	33	9,084
"	"	Sandstone stringers	...	...
"	"	Ophite	91	9,175
"	"	Melaphyre	79	9,254
"	"	Sandstone stringers	...	...
"	"	Ophite	148	9,402
"	"	Sandstone	4	9,406

Map		Rock	Thickness (Feet)	Subtotal (Feet)
Pl. 2	E-F	Melaphyre	41	9,447
"	"	Sandstone stringers	...	...
"	"	Melaphyre	52	9,499
"	"	"	21	9,520
"	"	"	10	9,530
"	"	"	94	9,624
"	"	"	107	9,731
"	"	Ophites	354	10,085
"	"	Melaphyre	39	10,124
"	E-F, D-E	Ophite	167	10,291
Pl. 1	D-E	Melaphyre	50	10,341
"	"	"	88	10,429
"	"	"	81	10,510
"	"	"	50	10,560
"	"	"	15	10,575
"	"	"	8	10,583
"	"	"	12	10,595
"	"	"	22	10,617
"	"	"	9	10,626
"	"	"	22	10,648
"	"	"	9	10,657
"	"	"	14	10,671
"	"	"	46	10,717
"	"	"	16	10,733
"	"	"	18	10,751
"	"	"	30	10,781
"	"	"	42	10,823
"	"	Sandstone stringers	...	...
"	"	Melaphyre	13	10,836
"	"	"	73	10,909
"	"	"	48	10,957
"	"	"	68	11,025
"	"	"	28	11,053
"	"	"	38	11,091
"	"	Sandstone	3	11,094
"	"	Melaphyre	42	11,136
"	"	Sandstone stringers	...	...
"	"	Melaphyre	33	11,169
"	"	Sandstone	1	11,170
"	"	Melaphyre	36	11,206
"	"	Sandstone	2	11,208
"	"	Melaphyre	16	11,224
"	"	"	26	11,250
"	"	Sandstone	1	11,251
"	"	Ophite	20	11,271
"	"	Sandstone stringers	...	...
"	"	Melaphyre	18	11,289
"	"	Sandstone (6–8 inches)	...	...
"	"	Melaphyre	22	11,311
"	"	Ophite	82	11,393
"	"	Melaphyre	45	11,438
"	"	"	8	11,446
"	"	Sandstone	2	11,448
"	"	Porphyrite	31	11,479
"	"	Amygdaloidal conglomerate	20	11,499
"	"	Porphyrite	109	11,608
"	"	Melaphyre	21	11,629
"	"	Porphyrite	14	11,643
"	"	"	55	11,698

Map		Rock	Thickness (Feet)	Subtotal (Feet)
Pl. 1	D-E	Porphyrite	38	11,736
"	"	Melaphyre	47	11,783
"	"	"	98	11,881
"	"	"	62	11,943
"	"	Amygdaloidal conglomerate	23	11,966
"	"	Ophite	56	12,022
"	"	Melaphyre	2	12,024
"	"	Sandstone	2	12,026
"	"	Melaphyre	6	12,032
"	"	"	64	12,096
"	"	"	92	12,188
"	"	"	127	12,315
"	"	"	64	12,379
"	"	"	51	12,430
"	"	"	31	12,461
"	"	"	27	12,488
"	"	"	133	12,621
"	"	"	42	12,663
"	"	"	16	12,679
"	"	"	30	12,709
"	"	"	37	12,746
"	"	"	14	12,760
"	"	"	12	12,772
"	"	Sandstone	12	12,784
"	"	Melaphyre	81	12,865
"	"	"	59	12,924
"	"	"	11	12,935
"	"	Felsite	122	13,057
"	"	Melaphyre	57	13,114
"	"	Sandstone (a few inches)	...	...
"	"	Melaphyre	68	13,182
Pl. 1	D-E, C-D	Melaphyre	36	13,218
"	C-D	"	47	13,265
"	"	"	9	13,274
"	"	"	10	13,284
"	"	"	30	13,314
"	"	Sandstone (6–8 inches)	...	...
"	"	Rhyolite	254	13,568
"	"	Diabase (Lester River sill)	963	14,531
"	"	Melaphyre	26	14,557
"	"	"	119	14,676
"	"	"	99	14,775
"	"	Sandstone	2	14,777
"	"	Mygdaloidal conglomerate	4	14,781
"	"	Melaphyre	25	14,806
"	"	"	107	14,913
"	"	"	90	15,003
"	"	Diabase (60th Avenue sill)	43	15,046
"	"	Porphyrite	149	15,195
"	"	Melaphyre	114	15,309
"	"	"	31	15,340
"	"	Sandstone	1	15,341
"	"	Rhyolite	622	15,963
"	B-C	Porphyrite	68	16,031
"	"	Diabase (48th Avenue sill)	132	16,163
"	"	Felsite	76	16,239
"	"	Melaphyre	168	16,407
"	"	Sandstone	1	16,408
"	"	Melaphyre	115	16,523

Map		Rock	Thickness (Feet)	Subtotal (Feet)
Pl. 1	B-C	Rhyolite	189	16,712
"	"	Felsite	125	16,837
"	"	Porphyrite	3	16,840
"	"	Rhyolite	16	16,856
"	"	Felsite	315	17,171
"	"	Melaphyre	4	17,175
"	"	Scoriaceous amygdaloid	10	17,185
"	"	Porphyrite	33	17,218
"	"	Sandstone	5	17,223
"	"	Porphyrite	29	17,252
"	"	"	73	17,325
"	"	"	31	17,356
"	"	"	111	17,467
"	"	"	45	17,512
"	"	"	85	17,597
"	"	Rhyolite	161	17,758
"	"	"	109	17,867
"	"	" (part of rhyolite flow under diabase)	14	17,881
"	"	Diabase (Northland sill)	31	17,912
"	"	Rhyolite	445	18,357
"	B-C, A-B	Diabase (Endion sill)	1,295	19,652
"	A-B	Porphyrite	101	19,753
"	"	Felsite	14	19,767
"	"	Melaphyre	12	19,779
"	"	Diabase	64	19,843
"	"	Melaphyre	151	19,994
"	"	Amygdaloidal conglomerate	12	20,006
"	"	Melaphyre	29	20,035
"	"	"	16	20,051
"	"	Porphyrite	45	20,096
"	"	Melaphyre	56	20,152
"	"	Sandstone	114	20,266
"	"	Porphyrite	90	20,356
"	"	Melaphyre	18	20,374
"	"	Sandstone	16	20,390
"	"	Melaphyre	52	20,442
"	"	"	21	20,463
"	"	Porphyrite	98	20,561
"	"	Melaphyre (6 inches; dense)	...	...
"	"	"	45	20,606
"	"	Sandstone	9	20,615
"	"	Melaphyre	14	20,629
"	"	"	34	20,663
"	"	Sandstone	20	20,683
"	"	Melaphyre	32	20,715
"	"	"	55	20,770
"	"	"	27	20,797
"	"	Porphyrite	32	20,829
"	"	Melaphyre	68	20,897
"	"	Porphyrite	84	20,981
"	"	"	83	21,064
"	"	Porphyrites, melaphyres, 1 felsite, 1 ophite (at least ten flows)	1,368	22,432
		Duluth gabbro	14,500	36,932
		Melaphyres and porphyrites (below Duluth gabbro)	2,500	39,432
		Basal sandstone (section 29)	50	39,482
		..............Unconformity	...	...
		Carlton slate — thickness unknown	...	...

Such a thickness calculation as this may be subject to certain errors. These are (1) errors in field observations, including undetected changes in dip, or duplication of beds by faulting, and (2) reckoning of apparent rather than real thickness where beds have a shingled, foreset structure.

Dip observations are available at short intervals over the whole section studied and show a progressive change which has been taken into consideration.

Study of the flow sequence and careful field search do not indicate that an appreciable duplication of beds, if any, had resulted from faulting. The absence of dip faulting is indicated by the persistence of individual beds along the strike.

As to the second source of error — that is, shingling of the layers — a minor amount of this may be possible, but it does not seem likely that any serious error is involved. According to the theory of a sinking lava plateau on which a level surface is maintained by successive outpourings of lava, the thickness of flows would be greatest near the center, decreasing toward the margins. Any thickness determined in a section away from the center of the basin would be less than the maximum.

Earlier estimates of the thickness of the Minnesota section of the Keweenawan have been from 17,000 to 18,000 feet, exclusive of the Duluth gabbro.[12] This figure apparently does not exclude the diabase sills. In the present report the thickness of the Keweenawan from the base (southwest of Duluth) to Two Harbors, exclusive of the gabbro, is 25,000 feet. (See the accompanying table.) If the remainder of the section, northeast of Two Harbors, is measured and the amount added to this figure (25,000 feet), the total will exceed the earlier estimate by somewhat more than 7000 feet.

CLASSIFICATION

Thin sections of a great many of the flows embracing all facies were studied. The microscopic characteristics are those common to the Keweenawan of the Lake Superior district. It seems desirable, therefore, to summarize the microscopic characteristics rather than repeat detailed descriptions available elsewhere. The basic Keweenawan flows are all properly classified as basalts, and various geologists working on Keweenawan Point have developed a megascopic classification useful in field work and used by the latest detailed report on the Keweenaw copper district.[13] The types recognized in the Duluth section include ophite, porphyrite, and melaphyre. Actually, thin sections of the Duluth basic flows, almost without exception, show a diabasic texture.

There has been considerable variety in usage of textural terms. Some use ophitic in a broad sense, that is, as equivalent to diabasic. Lane argued that ophitic should be restricted to designation of a mottled tex-

[12] C. R. Van Hise and C. K. Leith, *The Geology of the Lake Superior District* (United States Geological Survey Monograph 52, 1911), p. 418.

[13] B. S. Butler and W. S. Burbank, *The Copper Deposits of Michigan* (United States Geological Survey Professional Paper 144, 1929).

SUMMARY OF THICKNESS BY ROCK TYPES

Rocks	Thickness (feet)	Total (feet)
Basic extrusives		
Melaphyre	5,326	
Ophite	4,430	
Porphyrite	1,407	
Melaphyre and porphyrite, undifferentiated	3,868	
Melaphyre and ophite, undifferentiated	3,046	
		18,077
Acid extrusives		
Felsites and rhyolites	2,462	
		2,462
Inter-flow fragmental rocks		
Sandstone	198	
Amygdaloidal conglomerate	59	
Scoriaceous amygdaloid	10	
		267
Basal sandstone (Lower Keweenawan)	50	
		50
Total extrusives and related sediments		(20,856)
Intrusive rocks		
Duluth gabbro	14,500	
Diabase sills	4,126	
		18,626
Total thickness of Keweenawan measured		39,482

ture.[14] Diabasic texture, as here used, refers to tabular plagioclase crystals embedded in a matrix of coarser pyroxene, feldspar, magnetite, and accessory minerals. Vogt says of this texture, "The hyperitic (ophitic) texture of plagioclase crystal, with tabular development along (010) appears in gabbro rocks only when the latter contain at least 55 per cent plagioclase (labradorite)."[15] The tabular development of plagioclase is characteristic of all three facies of the Duluth basalts, but study of the norms of Broderick's analyses of Keweenaw Point flows shows that several are as low as 50 per cent feldspar. The lowest in the Kearsarge ophite contains only 42.85 per cent feldspar.

Melaphyre. In the rocks of Keweenaw Point the term *melaphyre* has been used for basic flows which correspond to simple basalts, that is, rocks with a very dense texture throughout. They form the most abundant type of flows in the Duluth section — nearly 50 per cent of the basic flows which can be clearly differentiated in the field.

The melaphyres vary from reddish brown to grayish or greenish black. The red color is a result of oxidation of the iron which may be due to the effect of gases in the flows or, in part, to later hydrothermal activity. Weathering may also be responsible for reddish flows, but this is usually

[14] A. C. Lane, *The Keweenawan Series of Michigan* (Michigan Geological Survey, Publication 6, Geological Series 4, Volume 1, 1911).

[15] J. H. L. Vogt, "The Physical Chemistry of the Crystallization and Magmatic Differentiation of Igneous Rocks," *Journal of Geology,* 29:426–43 (1921).

not the case alongshore where most weathered rock is rapidly eroded away. The reddish color is often more evident in the amygdaloidal zone.

Thin sections of melaphyres, as noted above, almost invariably reveal a fine-grained but definite diabasic texture, that is, lath-shaped plagioclase embedded in a matrix predominantly pyroxene.

The primary minerals of the melaphyres consist mainly of plagioclase, augite, magnetite, and ilmenite. Olivine is absent in most melaphyres although it was recognized in a few. Common alteration products are chlorite, hematite, epidote; less common are serpentine, kaolinite, limonite, carbonate, leucoxene. In the amygdaloidal portions there is some dense isotropic black glass, but this seems rare; most amygdaloidal rocks have a diabasic groundmass.

Rocks classified as melaphyres by examination in the field are occasionally found to contain small phenocrysts when studied in thin section. Such rocks might be classified as porphyrites if the classification were based on microscopic rather than megascopic characteristics. This serves to emphasize the fact of gradation between the porphyrites and melaphyres.

Porphyrite. Many of the Keweenawan flows are somewhat porphyritic. The phenocrysts are usually small feldspars, but these may vary up to an inch in length. Thin sections reveal only a little variation between the various porphyrite flows. The porphyritic character does not depend on the thickness of the flows, for even the amygdaloidal portions are porphyritic, but the nature of the groundmass may vary. Thin flows, such as a 6-foot flow exposed on shore 500 feet northeast of Lakewood Pumping Station, have a few plagioclase phenocrysts in a matrix which is partly diabasic but consists largely of a dense, opaque, glassy material. The porphyrites, in common with the other basalt flows, consist mainly of plagioclase, pyroxene, and magnetite-ilmenite. Olivine is only rarely recognizable, but some slides contain serpentine probably derived from olivine.

Some clustering of phenocrysts occurs in an occasional porphyrite, for example, in a thick flow about half a mile east of Lakewood Pumping Station. No flow in the Duluth section, however, could be classed as a glomeroporphyrite. The groundmass is much altered in many flows; hematite, chlorite, sericite, serpentine, and earthy isotropic material are the common alteration products. Dendritic forms of magnetite-ilmenite were observed in some slides. Chlorite is not only the most common alteration product but also the most abundant filling amygdules. Phenocrysts are usually much less altered than the groundmass, but considerable epidote occurs in feldspar phenocrysts of the first flow exposed northeast of Minnesota Point. On shore, opposite Thirty-fourth Avenue East, plagioclase phenocrysts are altered to a complex of carbonate, sericite, chlorite, and quartz.

In the more highly altered porphyritic flows, the pyroxene of the groundmass has almost entirely altered to chlorite, hematite, and other minerals. Even the feldspar phenocrysts may be badly clouded with epidote, sericite, kaolin, and hematite. A porphyritic flow exposed on the shore of Lake Superior at Thirty-eighth Avenue East is so red that it resembles a felsite, but the feldspar is plagioclase and the dense, more or less amorphous groundmass is colored by hematite. Quartz is lacking so the rock is, no doubt, only an altered basic porphyrite. The pervasive dusty hematite masks the true character of many Keweenawan igneous rocks and often makes field identification somewhat uncertain.

Ophite. The characteristic ophitic texture of many Keweenawan flows has been discussed in detail by Lane[16] and, as these characters are common to the Minnesota flows, there is no necessity for a review of the origin here. The texture is best exhibited on worn or weathered surfaces as a roughly circular mottling produced by crystals of pyroxene that enclose feldspar crystals. The center of thick flows, which cooled more slowly, have a much coarser mottling than the bottom and top where cooling was more rapid. Sandberg's measurements show that nearly 40 per cent of the basic flows of the Duluth area are ophites. Thin sections show that diabasic texture is characteristic throughout but stands out most prominently in large areas of pyroxene with poikilitic feldspar. While detailed quantitative data were not obtained, it seems evident from the many slides examined that olivine, as well as augite, is more abundant in the ophites than in the melaphyres and porphyrites. Some ophites appear to have a rather high content of magnetite and ilmenite. Magnetite in the more altered flows is often partly altered to hematite. Olivine is usually highly, or even completely, altered to serpentine, often with the separation of hematite resulting in red spots. Hisingerite also occurs as an alteration product, as does leucoxene. This emphasizes the mottled appearance of the rock. Reddish ophites are, therefore, rather common. Less commonly the pyroxene is also clouded with secondary hematite. In some specimens olivine may be almost destroyed, but the pyroxene remains relatively unaltered.

Modern analyses of the ophitic flows of the Minnesota Keweenawan are not available, but Broderick has published an elaborate series of analyses of the flows of Keweenaw Point on the south shore of Lake Superior.[17] It is probable that analyses of the Minnesota ophites would fall within the range of the 32 analyses given in Broderick's paper which show silica contents of from 46.04 to 50.34 per cent. Comparison of Broderick's analyses shows no consistent difference between melaphyre, ophite, and porphyrite. It seems evident that the cause of the variation in megascopic texture is not well understood and that the variation is not important in most respects.

[16] A. C. Lane, *The Keweenawan Series of Michigan* (Michigan Geological Survey, Publication 6, Geological Series 4, Volume 2, 1911).

[17] T. M. Broderick, "Differentiation in Lavas of the Michigan Keweenawan," *Bulletin of the Geological Society of America,* 46:503–58 (1935).

Acidic Flows. The acidic flows of the Keweenawan are practically always pink to brick red and have usually been referred to simply as felsites. Microscopic examination and chemical analyses prove that most, if not all, acidic flows are rhyolites. Some show quartz and orthoclase phenocrysts; others are simply felsitic and even under the microscope contain much isotropic material. The rhyolites are always conspicuously fractured on exposed surfaces and, because of this tendency, usually form small bays wherever present along the coast of Lake Superior. Along the streams entering the lake, narrow gorges with nearly vertical cliffs of loose jointed felsite are characteristic. This is well shown along the lower portion of the Lester River. Because of the fracturing, good exposures of

FIGURE 15. — Contact of basalt flow and thin rhyolite flow at the base of the Endion sill.

the felsites are relatively uncommon except along the streams and on shore. Flow banding is common in the felsites and often the banding is very irregular as if there had been complex folding during consolidation. Alteration and mineralization of the acid flows is common, calcite and fluorite being especially characteristic. Sandberg measured 2462 feet of felsites between the base of the Keweenawan and Two Harbors, which is about 12 per cent of the total thickness of flows. This is probably a fair estimate of the percentage for the entire Minnesota coast of Lake Superior.

There are no acidic flows beneath the gabbro. The lowest stratigraphically occurs at the base of the Endion sill (Figure 15). At places there is a gradational contact between the two which resulted from recrystallization of the flow near the acidic upper portion of the sill. There are a series of four felsite flows well exposed above the Endion sill alongshore and along Congdon Creek. Between this series of felsites and others at Forty-second Avenue East is a series of porphyrite flows. Northeastward alongshore acidic flows occur at intervals to a point above the Lester River diabase and opposite Mile Post 8 on the Duluth, Missabe, and Iron Range Railway. Northeast of this point, there are no felsites as far as Two Harbors, a distance of 18 miles. Other rhyolites are similarly irregularly distributed along the Minnesota coast to Grand Portage Bay.

Thin sections of most of the felsite flows have been examined, and chemical analyses are available of two. (See the accompanying table.) Silica is high — more than 70 per cent — in these two analyses and also in older analyses of felsite which occur farther northeast alongshore. Flows of intermediate composition are lacking. Dusty red feldspar and quartz form most of the rocks, with many variations of micrographic texture common. Enhedral feldspars may form a porphyritic texture, but often euhedral forms are scarcely larger than the quartz grains. A small amount

ANALYSIS OF FELSITES (RHYOLITES)

	1	2
SiO_2	75.48	71.12
Al_2O_3	12.30	12.58
FeO_3	2.54	5.20
FeO	.36	.15
MgO	Tr.	.08
CaO	.14	.58
Na_2O	3.43	2.85
K_2O	5.17	6.19
H_2O_4	.24	.22
H_2O	.04	.05
TiO_2	.21	.45
P_2O_5	.02	.03
MnO	.02	.06
CO_2	...	.18
	99.95	99.74
	Sp. Gr. 2.638	

1. Tischer's (Congdon) Creek, near 2nd Street, Duluth. S. S. Goldich, analyst.

2. Above Lester River sill. Mouth of creek on shore of Lake Superior. NE¼ NE¼, Sec. 34, T. 50 N., Rs. 12, 13 W. R. W. Perlich, analyst.

of magnetite is usually present and in some felsites is surprisingly abundant for such a highly siliceous rock. The primary ferromagnesian mineral was hornblende, but in most cases this has altered to a confused mass of chlorite and many other alteration products. Owing to the dusty hematite in the feldspar, it is often difficult, if not impossible, to determine the feldspars by the usual methods. The norm of the rhyolite exposed on Tischer's Creek just above the Endion sill shows roughly equal amounts of albite and orthoclase molecules. Only one feldspar can be recognized in most thin sections, and, therefore, it must be anorthoclase. The rhyolite above the Lester River sill has a ratio of orthoclase to albite of about three to two. This rhyolite is dark red and slightly porphyritic and contains apatite, fluorite, zircon, magnetite, chlorite, and hematite as accessory minerals and alteration products. Chlorite, sericite, hematite, and epidote are common alteration products found in most of the felsites.

Grout and Thiel investigated the heavy minerals of six felsites of the Duluth area. Magnetite, hematite, ilmenite, and leucoxene form the bulk of the heavy minerals thus obtained. Zircon, apatite, fluorite, and sphene form all but a negligible amount of the remainder.

The banded and spherulitic facies of the felsites are usually very fine-grained and often messy in appearance under the microscope; they contain much devitrified glass as well as alteration products. Recognizable primary minerals include only feldspar, quartz, and magnetite. Some specimens of rhyolite seem to contain only feldspar and quartz, the former stained red by much fine hematite diffused throughout the feldspar. Some well-banded specimens consist of bands or zones of very dense glassy material alternating with coarser quartz with small feldspar phenocrysts. In spherulitic rhyolites round aggregates of quartz and chalcedonic materials may be seen in thin section. In some slides the quartz varies from very fine grains to bladed forms and coarse grains. In some slides quartz obviously predominates and consists of aggregates of small anhedral grains which enclose the less abundant grains of feldspar. Highly porphyritic facies are uncommon but do occur. At the corner of Eighth Street and Twenty-second Avenue West is a rhyolite porphyry with phenocrysts of albite with the usual fine-grained groundmass of quartz and red feldspar.

Amygdaloidal Conglomerate. Several beds of a complex conglomeratic mixture of pebbles, boulders of amygdaloidal basalt, and to a lesser extent dense basalt with a sandy matrix occur between flows. The thickness is variable and probably differs greatly within short distances. The total thickness of the several beds is 59 feet. These beds, as a rule, not only represent the rough clinkery parts of the amygdaloidal zone (which is more or less broken and open and, therefore, subject to rapid erosion) but also serve as a trap for the sediment which is washed into the opening. There may be a gradual transition to simple amygdaloidal basalt, and the amygdaloidal conglomerates may well be considered as a hybrid, part igneous and part sedimentary.

Many thin sections of these deposits were examined. Several sections from a bed are usually necessary because the mixture is very irregular and blocks of amygdaloidal basalt a foot or more across are not uncommon.

A fairly typical occurrence is exposed near the Lakewood Pumping Station. The amygdaloidal portion is more or less normal amygdaloidal melaphyre with a diabasic texture and amygdules filled with chlorite. The sandy matrix consists of small, well-rounded grains of quartz and feldspar coated with limonite. Magnetite is fairly abundant and pyroxene and hematite also occur. The sand is therefore an arkose. The flow fragments vary from bed to bed and include melaphyres, porphyrites, and ophites. As would be expected, alteration products cloud the grains and often form coatings on them. Leucoxene, epidote, hematite, and limonite are common. Introduced calcite and, to a lesser extent, other minerals are a feature of some of these porous rocks.

Amygdaloidal conglomerates are a common feature of the sequence of flows in the Keweenawan copper district of Michigan, where they have been extensively studied and described.

Inter-flow Sandstones. The inter-flow sediments consist chiefly of fine-grained, uniform-textured sandstones (using that term to denote merely a consolidated sand). They are gray or buff to pinkish, thinly laminated, and some show cross-bedding similar to that seen in dunes. They are composed chiefly of disintegration products of the flows, with a little quartz, and possibly some tuffaceous material. Nothing which could be positively identified as organic remains was found. A few sandstones contain basal pebbles of the underlying amygdaloid, but many rest directly on the soft amygdaloids, without transitional phases.

About twenty inter-flow sandstones were found, only a few of which have a thickness greater than 3 feet — specifically, 5, 12, 16, 20, and 114 feet. The 114-foot bed occurs in Leif Ericsson Park, Duluth (Plate 1, A-B). It shows pronounced and irregular cross-bedding, is cut by a basaltic dike near the top, and ends in a fault of unknown, though probably small, throw which has not repeated the bed in outcrop.

Thin sections of most of the sandstones were examined. The grains are fairly well rounded in most occurrences, but a few have angular or subangular grains predominant. The most common minerals are quartz and feldspar, but grains of magnetite, hornblende, and pyroxene also occur. Most are dominantly feldspar, but some are fairly high in quartz. The fine matrical material looks cherty, that is, more or less cryptocrystalline. Alteration products are chlorite, epidote, carbonate, leucoxene, and hematite. Hematite commonly coats the sand grains, forming a reddish rock. This dusty coating of hematite and other alteration products often makes identification of the sand grains difficult. Some grains are rock fragments rather than individual minerals.

A thin bed of sediment exposed alongshore between east Eleventh and Twelfth streets consists mainly of a very fine-grained cherty material with coarser grains of epidote and magnetite. This seems more or less identical with the matrical material of some of the other sandstones.

Attempts to study the heavy minerals of these sandstones have not met with much success because of their complicated nature.[18] The sands are high in heavy minerals and the greater portion of the heavy fraction

[18] F. F. Grout and G. A. Thiel, "Studies of the Lake Superior Pre-Cambrian by Accessory-mineral Method," *Bulletin of the Geological Society of America*, 51:1507 (1940).

is a semi-transparent mineral that is 98 per cent dusty epidote and chlorite. The remaining 2 per cent is composed of grains of apatite, zircon, and pink garnet.

Basaltic Dikes. Forty or fifty basaltic dikes were observed, all except three of them in the western half of the section (Figure 16). There is an imposing similarity between all the dikes, which permits their collective description.

1. All have very dense, chilled borders with gradation of grain size toward the center. Dikes a few inches thick are dense throughout; those more than 10 feet thick have centers of fine-grained diabase.

2. None contains amygdules.

3. All show good columnar jointing perpendicular to the walls.

4. Those more than a foot or two thick have a tabular jointing parallel to their walls.

5. Few of them form a close, "fused" bond with the wall rocks.

6. Calcite veins occur in joint cracks and along the walls. Some of these contain laumontite, epidote, and pyrite also.

7. The walls are generally straight or gently curving, and branching is rare. In acid flows the dikes are less regular.

FIGURE 16. — Basalt dike in lava flow, lake shore at Seventh Avenue East, Duluth.

8. Opposite walls are generally parallel, irregularities in one wall being matched by corresponding features in the opposite wall.

9. Xenoliths are rare.

10. No primary flowage brecciation was noted.

11. Flow structure was not seen.

12. Contact effects on the wall rocks are weak.

13. A dark greenish-black color is common to all.

14. Practically all joint surfaces are coated with a dark greenish, chloritic material which shows slickensiding, though no net displacement occurs.

15. The composition is uniformly basaltic — labradorite, pyroxene, and iron oxides are the principal primary minerals.

16. Microscopically the texture is diabasic.

17. Phenocrysts are rare.

18. The thickness varies from a fraction of an inch to 30 feet or more. Most dikes are from 1 to 10 feet thick.

19. They are generally made conspicuous alongshore by differential erosion.

20. The dominant strike is a little east of north, the dip about 80° west.

The dikes cut all other rocks and wherever found show the characteristic features common to all.

Clastic Crevice Filling. At many places sandy stringers penetrate the lava flows, normally from the top down. Fackler has recently described the occurrence of these crevice fillings along the north shore of Lake Superior.[19] They are very irregular, with frequent branching and variation in thickness. Often they are associated with inter-flow sandstones or amygdaloid conglomerates, but some merely occur at the top of a flow.

Thin sections of many of the crevice fillings which occur alongshore from Duluth to Two Harbors were examined. Some of them are essentially identical in character with the inter-flow sandstones. The grains are well rounded and the principal minerals are feldspar, quartz, magnetite, pyroxene, and hornblende, all coated with hematite.

A good example of a stringer in a melaphyre flow just below a 4-foot sandstone bed may be observed just west of the mouth of the Talmadge River. The grains vary from well rounded to angular and consist of the minerals listed plus grains of rock fragments. A similar arkosic string occurs in an ophitic flow a few hundred feet east of the mouth of the river.

An unusual occurrence is that of a dike or stringer in the red rock (granitic) facies of the Lester River diabase sill. The sand grains in this case are mainly well-rounded quartz with a dense amorphous matrix which is probably kaolinite and leucoxene.

On shore at Forty-fourth Avenue East a stringer consists of well-rounded grains of quartz and feldspar largely altered to sericite with some leucoxene. At Fifty-sixth Avenue East another stringer consists principally of feldspar, high colored, with hematite. Small amounts of magnetite, limonite, chlorite, and epidote also occur.

Some of the stringers are dense, fine grained, and flinty in appearance. They appear to consist mainly of a very fine quartz mosaic, the grains being too small to show rounding.

THE DULUTH GABBRO[20]

The Duluth gabbro is one of the largest basic intrusives known. It extends from Duluth northeastward as a great crescent-shaped mass at the surface. The eastern point intersects the lake shore east of Hovland. The mass intrudes the Keweenawan rocks at both ends and has flows above it along its entire length, but the floor transgresses the various formations of the pre-Cambrian so that it is in contact with rocks varying from Keewatin to Keweenawan in age. The mass was termed a lopolith by Grout.[21] The term is derived from Greek words meaning basin and stone, referring respectively to shape and composition. A lopolith is

[19] W. C. Fackler, "Clastic Crevice Fillings in the Keweenawan Lavas," *Journal of Geology*, 49:550–56 (1941).

[20] The exposures referred to in this section are shown on Plates 4 to 19.

[21] F. F. Grout, "The Lopolith; an Igneous Form Exemplified by the Duluth Gabbro," *American Journal of Science*, 46:516 (1918).

defined as a large, lenticular, centrally sunken, generally concordant, intrusive mass with its thickness approximately one tenth to one twentieth of its width or diameter.

At Duluth the gabbro forms a prominent bluff from the Morgan Park steel plant to Mesaba Avenue (Plates 8 and 11). Northeast of Mesaba Avenue the top of the gabbro trends inland, but the bluff more nearly parallels the shore. It is evident that metamorphism of the flows above the gabbro has made them resistant to erosion, and they form the bluff to Chester Park. Beyond Chester Creek valley the bluff is less prominent and is partly a result of the resistance of the Northland diabase intrusive. The gabbro has no part in the topography alongshore beyond Duluth.

The base of the gabbro has been traced fairly closely from the exposure near the railroad tracks in Sec. 33, T. 49 N., R. 15 W., north and slightly westward to the north line of the township in Sec. 5. There is, however, not a single exposure of the contact except that near the railroad tracks. Outcrops are scarce farther north in T. 50 N., but the base of the gabbro has been rather precisely located by magnetic methods up to its exposure at the east end of the Mesabi Range.[22] The contact trends nearly due north across the west side of T. 50 N., R. 15 W., and slightly east of north across Tps. 51 and 52 N., R. 15 W.

The upper contact with the lava flows may also be traced by outcrops in and near the city but it is located less exactly on the upland where outcrops are sparse.

In downtown Duluth the easternmost outcrops of gabbro occur on the east side of Mesaba Avenue just north of Michigan Street (Plate 11). The contact is located beneath the center of First Street, 160 feet east of Sixth Avenue West. From this point northward the position of the top is indefinite up to Fourth Avenue West and the projection of Seventh Street, where exposures locate the contact very closely with a red rhyolite flow above the gabbro. The contact is somewhat wavy, but it is not far from Fourth Avenue West up to Thirteenth Street, where it turns about due north. Outcrops are sparse, but the contact may be seen just north of Upham Road and farther north at Kennebec and Hawkins streets and back of Villa Scholastica. On the north side of the school grounds the contact turns sharply eastward but resumes its northward trend again to the outcrops at Kenwood Avenue and Victoria Street. Here it turns definitely northeastward to trend diagonally across Forest Hill Cemetery. Here it again turns northward approximately along New Market Avenue to the city limits.

Beyond the city limits the outcrops become very sparse, but in a general way the contact is known to cross T. 51 N., R. 13 W., diagonally, and then cross T. 52 N., R. 13 W. to Sec. 1 in the northeast corner, where it is located between outcrops of rhyolite near the south line of the

[22] G. M. Schwartz, "Tracing the Duluth Gabbro Contact with a Magnetometer," *Economic Geology,* 39:224–33 (1944).

section and outcrops of gabbro half a mile to the north along the Sucker River. In general the contact is irregular and more or less gabbro has worked into the flow hornfels. Part of the irregularity is perhaps due to inclusions of hornfels in gabbro that may not always be recognized because of covered areas.

The flows immediately above the gabbro are metamorphosed for several hundred feet at the surface.[23] The most conspicuous change is textural because the flows are recrystallized to a hornfels with only a moderate variation in grain size. The fine, granular texture is a result of the tendency of the pyroxene, olivine, and magnetite to assume a globular, essentially equidimensional form. The rhyolites recrystallize to nearly equigranular quartz, red feldspar, and magnetite with subordinate ferromagnesian constituents, but there is little tendency to the globular form.

The most intensely recrystallized basalt occurs as inclusions in gabbro at the quarry near the Fifty-seventh Avenue Station at Duluth. An analysis of this rock indicates that the composition is much like that of the basalt flows, except that titanium and ferrous iron are high, suggesting an addition of these constituents from the gabbro magma.

The gabbro mass shows many variations, which have been described in considerable detail by Grout in the papers cited in the Chronological List of Publications. The detailed mapping of outcrops in connection with this report indicates possibly an even greater complexity than described by Grout — not in additional facies but in admixture of known facies.

Near the floor there are layers of peridotite, but they are neither extensive nor conspicuous. In fact, this facies is usually covered by glacial drift except along the Duluth, Winnipeg and Pacific Railway in Sec. 33, T. 49 N., R. 15 W. Locally there are small concentrations of titaniferous magnetite, but quantitatively these are insignificant. The principal facies of Duluth is a banded gabbro and olivine gabbro that varies to troctolite. Banded troctolite is conspicuously exposed along Skyline Parkway around Bardon's Peak above the steel plant (Figure 17). The more normal gabbro facies commonly displays a very coarse mottling.

The upper portion of the gabbro mass at Duluth is highly feldspathic. Grout estimated that, as a whole, it contains 80 per cent plagioclase and that large parts of it are anorthosite with nearly 100 per cent plagioclase. It forms an early facies that was considerably disturbed by the later, more normal gabbro. It is this relationship, no doubt, that accounts for much of the complex mixture of facies seen in scattered outcrops.

In general the banding in the gabbro strikes north to northeast and dips 10° to 30° E. and SE., thus conforming to the general structure of the Lake Superior syncline. Locally, however, the orientation of the bands varies greatly. At a few places discordance of dips in one zone with that

[23] G. M. Schwartz, "Metamorphism of Extrusives by Basic Intrusives in the Keweenawan of Minnesota," *Bulletin of the Geological Society of America*, 54:1211–26 (1943).

in another suggests cross-bedding, for example, along Highway 61 at the projection of Bristol Street. The banding in the lower part of an outcrop south of the highway dips about 17° SW., whereas the bands above dip 20° NE.

Not of large volume at Duluth, but of much interest, are various red granite facies grading at places to pegmatite. This "red rock," as it is usually called, forms a large belt in the central portion of the crescent-shaped mass in Lake and Cook counties, but near Duluth it occurs in large and small patches and dikes.

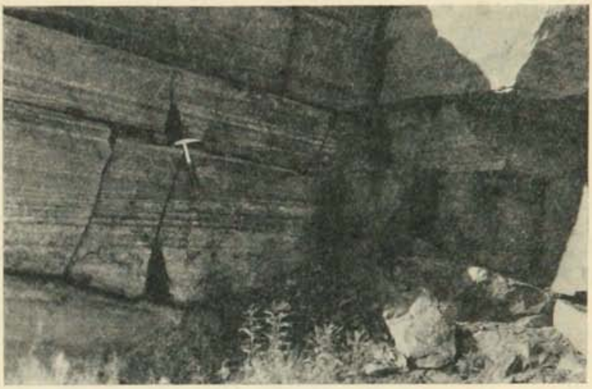

FIGURE 17. — Banding in Duluth gabbro, Skyline Parkway, Bardon's Peak, Duluth.

Convenient places to examine typical exposures are in Lincoln Park and in an abandoned quarry at Thirteenth Avenue West. Such granitic or pegmatitic patches are fairly common in the basalt hornfels near the top of the gabbro and also along the base. At places isolated intrusions of the granite occur near the top of the gabbro and in the flows.

Some of the more extensive of the red rock intrusions are at Woodland Avenue and Hartley Road, along Amity Creek west of New Market Road, north of Forest Hill Cemetery, and west of Howard Road in Sec. 36, T. 51 N., R. 14 W.

As a rule the gradation from gabbro to red granite is abrupt; the gray gabbro gives place to a bright red rock, but there are no intermediate minerals — simply the minerals of the gabbro and mainly the quartz and red feldspar of the red granite. At Lincoln Park the irregular patchy nature of the gabbro is a result of interstitial red granite or granophyr that grades off into irregular stringers. The granite stringers are definitely later but do not have chilled contacts, so they must have been intruded into hot gabbro.

At Thirteenth Avenue West, in an abandoned quarry, granite intrudes and evidently has shattered anorthosite and assimilated the fragments to some extent.[24] There is not a true gradation from one to the other and the red rock and anorthosite did not differentiate from the same magma. The significance of this occurrence in petrologic theory is emphasized in the paper cited.

Diabase Intrusives

The Keweenawan lava flows and sediments of the north shore of Lake Superior are intruded by a great number of diabase sills, dikes, and irregular masses of diabase. These are collectively known as the Beaver Bay Complex, from the name of the largest sill.

There are many of these intrusives, particularly sills in the Duluth area (Plates 11, 13, and 14), and the three most prominent have been studied in considerable detail. After careful field work, a thorough microscopic and chemical study was made in the laboratory. The laboratory work was generously aided by a grant from the Geological Society of America. The details are given in a separate paper,[25] but the more important points are covered in this chapter. Descriptions of other sills in the area between Duluth and Two Harbors are also included.

The smaller intrusives are composed entirely of diabase, but the larger masses seem to have been able to segregate to a point where at least a thin red rock (granite) appears in the upper portion. This is true mainly for the three sills in the city of Duluth.

It is perhaps desirable to treat the various intrusives in a systematic order; accordingly, they are described beginning with the upper gabbro contact at Mesaba Avenue in Duluth and taking each sill in order northeastward to the edge of the area at Two Harbors.

SILL AT SECOND AVENUE WEST

The sill closest to the gabbro is unknown from surface exposures but was encountered in the trunk sewer tunnel along First Street about 150 feet west of Second Avenue West. This point is 340 feet stratigraphically above the gabbro, and the sill is computed to be about 125 feet thick. It consists mainly of fairly coarse diabase with irregular areas of a red rock facies beneath Second Avenue West. The diabase is cut by numerous small seams of gouge; slickensides were also observed, so that fracturing with some subsequent movement was evidently common.

For some distance above this sill there are no intrusives in the flows, except several small basalt dikes exposed along the shore between Minnesota Point and Fifteenth Avenue East.

ENDION SILL

The Endion sill, named from Endion Station in the city of Duluth, is separated from the gabbro by 2780 feet of flows and diabase. The base

[24] F. F. Grout and W. W. Longley, "Relations of Anorthosite to Granite," *Journal of Geology*, 48:133–41 (1935).

[25] G. M. Schwartz and A. E. Sandberg, "Rock Series in Diabase Sills at Duluth, Minnesota," *Bulletin of the Geological Society of America*, 51:1135–72 (1940).

is exposed on shore at Sixteenth Avenue East and the top just east of Twenty-sixth Avenue East (Figure 15). The top is also exposed on Tischer's Creek a short distance to the northeast. The gabbro transgresses the flows at a large angle so that 2 miles to the north it is probably in contact with the Endion sill, but glacial deposits cover the contact. Farther north the nearest exposures to the top of the gabbro are diabase.

The flows which the Endion sill intrudes are mainly melaphyres and porphyrites but they include thin felsites and are cut by a few narrow, dense basalt dikes.

The Endion sill is about 1300 feet thick and is intruded into or below a thick rhyolite flow. At its base the diabase overlies about 2 feet of rhyolite which in turn overlies a basalt flow.

The Endion sill is typical of the thicker sills in the Keweenawan flows and Huronian slates of the north shore of Lake Superior. The various facies often grade from one to another, and those selected for chemical analysis and microscopic study are representative of the various gradations. Megascopic appearance is not always a good guide to significant differences which show up on detailed microscopic and chemical investigation. Six samples of the Endion sill and one of the overlying rhyolite were selected for analysis and microscopic study.

The base of the sill is well exposed on shore at the foot of Sixteenth Avenue East. At the contact the diabase is chilled and contains a few scattered large plagioclase phenocrysts.

This dense zone is not over 6 inches thick and grades upward to the typical diabase. Its thinness suggests the possibility that it is a thin layer of a basalt flow, but detailed examination led to the opinion that it is the chilled border of the sill.

The diabase of the lower part of the sill is black, massive, and ophitic, and blocky jointing is at places rudely columnar. The diabase is very coarsely ophitic (luster mottled) at places, and areas of pyroxene an inch or more across were observed enclosing lath-shaped feldspar crystals. Pegmatitic diabase patches were also noted in the lower portion of the diabase, and fairly dense stringers of red rock occur in otherwise typical diabase.

The gradation from diabase in the lower part to granitic rock at the top is not uniform, but much of the gradational zone shows a confused mixture of diabase and the red acidic facies, probably somewhat later in solidification if not in emplacement.

The presence of fairly dense red rock stringers well down in the sill suggests the existence higher up of acidic liquid at a time when a substantial portion of the sill had crystallized as diabase. Interstitial micropegmatite also probably indicates a later acidic residue. In the vicinity of Twenty-first Avenue East the diabase grades almost imperceptibly into a dark red facies. The gradation to a more typical red rock takes place between Twenty-first Avenue and Twenty-second Avenue East.

The red rock (granite or granophyr) facies constitutes perhaps the upper fourth of the sill. The diabase below it contains small interstitial areas of red feldspar. The red facies ranges from a dark reddish rock which somewhat resembles diabase to a typical red rock or granophyr.

The intermediate or dark red facies forms a considerable portion of the sill and grades to both the more basic and the more acidic varieties, as may be readily observed alongshore. It is cut by stringers of the most acidic (red) facies, and small red segregations occur irregularly throughout. Thin sections and chemical analyses show that many dark red facies are rather typical granites.

Near the rhyolite roof there is a very red zone, representing the most acidic facies in the sill. On shore the granite-rhyolite contact is gradational, metamorphism of the rhyolite by the granite having recrystallized the rhyolite so that it is difficult to distinguish the intrusive granite from the rhyolite host. On Tischer's Creek a few blocks north from the shore, and along the strike, the rhyolite has been less thoroughly recrystallized and the contact is readily located within narrow limits. A hand specimen collected by Frank F. Grout is half rhyolite and half red granite.

Dense basalt dikes cut the diabase and red rock at places. Thin sections of the analyzed specimens were studied and detailed descriptions are given in the paper previously published,[26] so only a summary is included here.

The rock near the base is massive, black when fresh, and has a fairly coarse diabasic texture with large pyroxenes up to 2.5 mm. across, enclosing labradorite crystals and rounded inclusions of primary olivine now much altered to an aggregate of uralite, chlorite, serpentine, and talc. Olivine originally made up about 10 per cent of the rock. The labradorite (Ab_{40} An_{60}) remains notably fresh. It is estimated to constitute 65 per cent of the rock. The lath-shaped crystals average about 0.10 mm. by 0.28 mm. There are a few feldspar crystals which are large compared to the averages (0.1 mm. by 0.9 mm.) and result in a faint porphyritic texture. The fresh rock was clearly olivine diabase.

Some of the rocks near the base have undergone considerable hydrothermal alteration; the labradorite, however, is unaffected, except for penetration by chlorite along the cleavage.

Somewhat above the middle of the sill, the rock is superficially much like the lower part, but detailed study, both under the microscope and by chemical means, shows that there is less olivine, a small percentage of quartz, and a correspondingly higher silica content.

The upper 200 feet or so of the sill, consisting of dark red granitic rock, looks like syenite in hand specimen. Plagioclase (mainly albite) and orthoclase are abundant. Some feldspar crystals are zoned, and much micropegmatite is interstitial to the feldspar crystals and to a small extent seems to have attacked them. The normative plagioclase is oligoclase.

[26] Schwartz and Sandberg, "Rock Series in Diabase Sills at Duluth, Minnesota."

Quartz is abundant. Much of the feldspar is red with dusty hematite and also contains disseminated sericite. Pyroxene is partly altered to uralite and chlorite. Calcite and serpentine also occur. Feldspar has been penetrated and slightly replaced by chlorite. Magnetite occurs as large grains and crystals, and pyrite was noted replacing one large grain.

This rock illustrates a feature shown by many of the dark granite facies of the sills, an abundance of coarse magnetite-ilmenite. Even when not particularly abundant, the magnetite-ilmenite occurs as relatively large grains. The norm shows 6.99 per cent magnetite and ilmenite, thus confirming the microscopic observations.

At places the granitic facies is characterized by long needles of hornblende, many of them replaced by an aggregate of alteration products. The individual needles range from 5 to 15 mm. in length, and sheaflike aggregates of needles up to 3 inches long were observed.

Nearer the top the rock is decidedly red and a sample representing typical red rock was taken from an outcrop on shore opposite Twenty-seventh Avenue East and within a few feet of the upper contact of the sill with rhyolite. The texture is fine granitoid, porphyritic, and micrographic. Albite and orthoclase constitute about 70 per cent of the rock. Dusty crystals of feldspar (0.3 by 1.1 mm.), some zoned, occur in a groundmass of mainly graphic quartz and feldspar with small amounts of fine-grained pyroxene (0.12 mm.) and magnetite. Alteration is not extensive, but pyroxene has partly altered to chlorite, and small amounts of hematite, sericite, and introduced carbonates also occur. The micrographic quartz and feldspar have attacked the feldspar crystals to a slight extent. The large amount of dusty hematite makes it difficult to determine much of the feldspar. The fact that the soda-potash ratio is three to four suggests an intermediate feldspar, since only a little albite can be recognized.

NORTHLAND SILL

The Northland sill is separated alongshore from the Endion sill by 445 feet of rhyolite, presumably a single flow. The Northland sill is much more irregular in plan view than most of the sills in the Duluth region. It is exposed on the shore of Lake Superior opposite Thirtieth Avenue East and crosses Tischer's Creek in Congdon Park at Thirty-third Avenue East (Plate 11). It is only 31 feet thick on the shore, where it consists entirely of diabase. The sill strikes about north-south and dips 17° E. A mile north of the shore, just west of the club house of the Northland Country Club, it is many times as thick and includes a granite facies. The area of outcrop thickens rapidly so that along the Skyline Boulevard in Sec. 6, T. 50 N., R. 13 W., there are abundant exposures on a high ridge extending over a width of 1600 feet, and the total width of the sill may be as great as 3000 feet, which would indicate a thickness of 1026 feet calculated on the basis of an average dip of 20°.

The relation of the granite to the diabase in this sill is not that of a zone along the top as is usually true of the Endion and Lester River sills, instead the granite is found irregularly in the midst of the diabase as shown on Plate 1. Particularly good exposures of the sill occur where the gorge of Lester River cuts through the sill. Here, too, granite and diabase occur in confused relation, and diabase is in contact with rhyolite at the top of the sill.

Along the strike of the sill northeast of the Lester River are exposures of diabase and granite which are nearly continuous for about a mile. The ridge is mainly diabase, but granite occurs low on the west side at places. Another exposure occurs half a mile farther north in the SE¼, NW¼, Sec. 21, T. 51 N., R. 13 W. Still farther northeast for several miles, thick red lake clays and terminal moraine deposits cover the rocks.

Several diabase exposures in the northwest part of T. 52 N., R. 12 W., may be correlated with the Northland sill.

The Northland sill, as exposed on the shore at Thirtieth Avenue East, is fresh diabase, some showing conspicuous columnar jointing and a chilled zone at both bottom and top. To the north, as noted above, a confusion of granite in diabase appears as the sill widens greatly. For the petrographic and chemical studies it was not possible to select specimens in order of increasing acidity from the base to top of the sill as was done for the Endion and Lester River sills. Samples from five different facies were therefore selected from various positions in the intrusives and these show a similar series.

The rock exposed on shore consists of a medium-grained, massive, black diabase with 60 per cent labradorite, 20 per cent pyroxene, and 15 per cent altered olivine. Magnetite-ilmenite completes the list of primary minerals. Pyroxene is partly altered to tremolite and olivine largely to iddingsite.

Other facies show varying amounts of quartz and increasing amounts of orthoclase, with the pyroxene and hornblende more abundant than is usual in typical granites.

SILL AT FORTY-EIGHTH AVENUE EAST

Along the shore of Lake Superior opposite Forty-eighth Avenue a diabase sill about 132 feet thick is well exposed, dipping 20° E. with felsite below and porphyrite above. Inland outcrops occur at intervals for several blocks to the northeast and again on the west branch of the Lester River approximately 1½ miles to the northeast.

At the upper contact the diabase is fine grained and the porphyrite flow is baked and cracked near the contact. A thin section of the diabase of the interior of the sill shows the usual diabasic texture. Labradorite and augite comprise the bulk of the rock, but magnetite-ilmenite is an important accessory and apatite also occurs. Serpentine occurs as a fringe along the borders of the labradorite crystals. In thin section the diabase at the contact with the underlying rhyolite consists of a dense, translucent, fine-grained mass with rounded quartz grains.

LESTER RIVER DIABASE SILL

The Lester River diabase sill was named from its outcrop on Lake Superior just west of the mouth of the Lester River near the east end of the city of Duluth (Plates 13 and 14). Its thickness on Lake Superior is given by Sandberg as 963 feet.[27] The strike is about N. 18° E. and the dip 20° SE.

The sill is underlain by a melaphyre flow estimated as 26 feet thick. A narrow covered zone conceals the exact contact. Specimens from an exposure nearest the base are fine to medium diabase and show no evidence of chilling and suggest that they do not represent the actual base. The exposures are practically continuous alongshore from this outcrop to the contact with the thick rhyolite flow above. Prominent dip joints near the base strike N. 15° E. and dip 20° SE.

The general extent and exposure of the Lester River sill is well shown by the outcrop map. It produces a low rocky coast. It rises gradually with abundant exposures along a more or less dip slope in and north of Sec. 4, T. 50 N., R. 13 W.

In the northeast corner of Sec. 33, T. 51 N., R. 13 W., the diabase forms a southward-facing bluff at the end of a ridge which was traced for more than 10 miles northeasterly. It is interrupted by the major stream valleys, and small streams originate on and flow down the dip slope. The ridge shows mainly outcrops of the massive and resistant diabase facies. Some stream crossings have exposed the sill extensively, particularly the acidic facies. It is noteworthy that, when followed north, the sill in conformity with the flows swings gradually more easterly. The strike on Lake Superior is about N. 18° E. In T. 52 N., R. 12 W., it is close to N. 45° E.

The Talmadge River exposes both the basic and acidic facies. The usual coarse diabase is well exposed on the ridge on both sides of the valley. The base of the sill is concealed by the red clays deposited in the valley by glacial Lake Duluth. Small exposures of diabase occur about one eighth of a mile downstream from the west line of Sec. 14, T. 51 N., R. 13 W. East of the diabase is a dark granitic facies which grades to a granophyr diabase, which in turn grades downstream into dark granitic facies and thence into the typical red rock exposed near the bridge at the center line of Sec. 14. Closely spaced joints in these exposures strike N. 20° E. and dip 13° SE. The upper contact is also covered, but rhyolite and basalt flows are exposed only a short distance from the granite.

Northeast of the Talmadge River the diabase is again well exposed. The French River exposes only one outcrop which is normal diabase. The

[27] A. E. Sandberg, "Section across the Keweenawan Lavas at Duluth," *Bulletin of the Geological Society of America*, 49:804.

Sucker River, still farther northeast, has extensively exposed basalt flows which appear to lie below the Lester River sill, but the sill is represented only by granophyr ranging from rather dark brown to the typical red facies. This occurs where the lower portion of the sill would be expected. Northeast of the Sucker River the diabase crops out on a series of isolated hills along the strike. A road cut exposes a black medium-coarse diabase-gabbro with blocky jointing.

A high knob and the stream valley of the west branch of the Knife River also expose the acidic facies. Farther northeastward exposures are scarce; and although those seen are nearly all granite it is not safe to conclude that the sill is composed entirely of granite. A broad valley floored with glacial lake clay masks exposures beyond Sec. 2, T. 52 N., R. 12 W., and the sill has not been recognized across the valley.

The lower contact of the sill is not exposed, but a somewhat baked amygdaloidal flow is exposed not more than 20 feet from the nearest diabase. Exposures are almost continuous alongshore across the full width of the sill. The main diabase is conspicuously mottled. The lower half appears uniform except for small red interstitial patches in the basal portion.

Near the middle of the sill are many 1-inch dikelets and segregations of red rock. In the upper portion red zones are related to fractures in a mixed and greenish rock. There is in reality little difference between the red and green phases except in the amount of oxidation of iron. The acidic zone is not clearly demarcated but is confused from the lowest appearance of red material to the contact of the rhyolite which is not readily located because of recrystallization. Small dense basalt dikes cut the sill, and several clastic dikes were observed in the granitic facies. The clastic dikes contain well-rounded quartz grains as well as fragments of several kinds of rock.

The microscopic characteristics of the rocks of the Lester sill are much like those of the Endion and need not be described in much detail. The basal diabase differs from the Endion in that it carries a small amount of quartz and feldspar as micropegmatite and no specimen was examined which lacked at least some quartz. The basal facies consists mainly of andesine and pyroxene, but the central diabase contains mainly labradorite and pyroxene.

The main red rock facies is dark and coarsely granitoid with micrographic quartz and feldspar. The feldspars are plagioclase, orthoclase, and microcline. Magnetite-ilmenite is notably abundant for a granitic rock, though this condition is found in many Keweenawan red rocks of Minnesota.

At places the acidic portion of the sill has a greenish-gray color and appears more basic, but thin sections and chemical analyses show that the color is misleading since it is due to small amounts of chlorite.

STONY POINT INTRUSIVE

The most irregular intrusive, and also the most difficult to interpret as far as shape is concerned, occurs on the shore of Lake Superior at Stony Point in Sec. 2, T. 51 N., R. 12 W., extending northeast to Knife Island in Sec. 31, T. 52 N., R. 11 W., a distance of roughly 2½ miles (Plates 13 and 17).

According to Sandberg's estimates, this intrusive occupies a distance alongshore equivalent to a stratigraphic thickness of 1598 feet. One of the remarkable features of this intrusive is that it has a visible continuity along the strike of less than 2 miles. Thus, it is not as regular a sill as the Lester River sill, which can be traced inland for 15 miles.

The base of the intrusive is exposed just west of the outermost projection of Stony Point, where it overlies a flow. The diabase is abundantly exposed alongshore and for about half a mile inland throughout Sec. 1, T. 51 N., R. 12 W. In the northeast portion of this fractional section a flow is exposed with an approximately normal dip and strike (N. 28° E., 15° SE.). The upper contact is not exposed, but diabase and flows are exposed within a few hundred feet of each other in Sec. 31, T. 52 N., R. 11 W. Knife Island and a series of small exposed rocks are lined up in such a manner as to suggest the existence of a dike with a trend of about N. 55° E.

A thin section of the rock from near the base of the intrusive shows a diabasic texture with labradorite making up about 50 per cent of the slide and augite with a small amount of olivine fully 40 per cent. Magnetite-ilmenite makes up 5 per cent and the remaining 5 per cent consists especially of blue-green fibrous iddingsite (serpentine) with some chlorite and epidote.

In the upper part of the sill coarse pegmatitic diabase stringers occur. Aside from the coarse grain the material is much like diabase except that the feldspar is andesine instead of labradorite.

The Stony Point sill has inclusions of anorthosite near the base on the west side of Stony Point.[28] There are several boulder-like masses but only two are above water level. The larger is about 12 feet across and the smaller about 4 feet. They have the typical rounded form of many of the anorthosite inclusions, which are so abundant in the diabases of the north shore of Lake Superior in Lake County.

CHEMICAL COMPOSITION OF THE DIABASE SILLS AND ASSOCIATED ROCKS

The differentiation of some of the sills at Duluth into diabase in the main portion and a granite at the top makes them of more than passing geological interest. As an aid in determining the exact differences between parts of the sills and explaining the possible origin of these differences, several rock samples were carefully selected from bottom to top

[28] F. F. Grout and G. M. Schwartz, *The Geology of the Anorthosites of the Minnesota Coast of Lake Superior* (Minnesota Geological Survey Bulletin 28, 1939), p. 63.

ANALYSES OF THE DULUTH SILLS

Sample No.	Endion Sill						Flow	Northland Sill					Lester River Sill									Flow
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
SiO_2	47.25	.....	52.42	61.46	.....	61.07	75.48	47.50	58.06	58.01	62.85	63.33	54.86	51.62	50.46	.....	58.88	56.76	61.22	.....	.....	71.12
Al_2O_3	15.00	.....	12.66	13.22	.....	13.66	12.30	12.94	13.09	13.63	13.10	12.99	11.92	11.39	16.90	.....	11.84	12.55	12.30	.....	.....	12.58
Fe_2O_3	2.64	5.97	3.90	3.08	4.53	3.04	2.54	3.94	3.34	4.59	2.71	2.87	5.04	4.94	4.68	3.37	6.82	4.70	9.51	1.96	5.71	5.20
FeO	11.09	9.37	9.55	5.42	2.57	5.54	.36	11.52	7.22	5.19	5.56	5.12	10.32	12.94	6.47	1.75	5.63	8.04	2.93	2.60	.56	.15
MgO	6.52	.....	3.74	2.00	.....	2.48	Tr.	5.62	2.05	3.05	1.40	2.21	1.53	3.00	4.01	.....	2.06	3.57	1.36	.....	.....	.08
CaO	8.40	.....	5.16	2.96	.....	2.36	.14	8.38	4.78	3.63	3.31	2.05	5.84	6.36	8.45	.....	3.63	1.75	1.46	.....	.....	.58
Na_2O	2.52	2.03	3.01	3.33	3.50	3.40	3.43	2.39	3.48	4.23	3.51	3.97	2.96	2.59	2.82	2.60	2.82	2.76	3.24	2.93	2.89	2.85
K_2O	.81	1.17	2.44	4.30	4.59	4.10	5.17	1.07	3.02	3.30	4.02	3.52	2.25	2.03	1.21	5.48	4.07	3.09	3.84	5.75	5.87	6.19
H_2O+	1.63	.....	2.00	1.24	.....	1.79	.24	1.31	1.48	1.02	1.08	1.25	1.68	1.32	1.63	.....	1.18	3.06	1.05	.....	.....	.22
H_2O-	.35	.....	.80	.32	.....	.45	.04	.68	.39	.52	.16	.58	.53	.78	1.28	.....	.58	1.16	.32	.....	.....	.05
TiO_2	2.89	.....	2.66	1.37	.....	1.37	.21	3.74	2.16	2.14	1.59	1.55	1.97	2.26	1.64	.....	1.38	1.62	1.62	.....	.....	.45
P_2O_5	.56	.....	1.14	.40	.....	.48	.02	.69	.70	.41	.40	.37	.66	.54	.42	.....	.41	.55	.54	.....	.....	.03
MnO	.21	.....	.25	.18	.....	.15	.02	.22	.17	.19	.14	.16	.26	.30	.17	.....	.20	.33	.28	.....	.....	.06
CO_2	.....	.....	.....	.53	.....	.20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.58	.....	.11	.....	.....	.18
Total	99.87	.....	99.73	99.81	.....	100.09	99.95	100.00	99.94	99.91	99.83	99.97	99.82	100.07	100.14	.....	100.08	99.94	99.78	.....	.....	99.74
Sp. Gr. t°/4°	2.965	.....	2.864	2.738	.....	2.718	2.638	2.982	2.818	2.804	2.767	2.728	2.891	2.962	2.818	.....	2.804	2.753	2.797	.....	2.694	2.681

NORMS

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Q	.....	.....	13.86	16.20	.....	15.78	35.76	2.64	13.56	10.08	17.58	18.30	15.6	9.60	6.06	.....	17.82	17.22	22.08	.....	.....	29.94
Or	5.00	.....	14.46	25.58	.....	24.46	30.58	6.12	17.79	19.46	23.91	20.57	12.79	12.23	7.23	.....	24.46	18.35	25.58	.....	.....	36.70
Ab	20.96	.....	25.15	28.30	.....	28.82	28.82	20.44	29.34	35.61	29.87	33.54	24.63	22.01	23.58	.....	23.58	23.58	27.25	.....	.....	24.10
An	27.24	.....	17.79	8.34	.....	7.78	.56	20.85	11.12	8.34	7.78	7.23	4.17	13.34	30.02	.....	7.51	5.00	4.17	.....	.....	1.67
Ca	.....	.....	.....	1.20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	1.30	.....	.....	.....	.....	.40
Di	9.12	.....	16.60	.46	.....	.....	.....	13.33	6.99	5.75	5.13	.46	17.52	11.79	7.42	.....	3.43	8.71	.....	.....	.....	T.
Hy	23.2	.....	.....	10.31	.....	11.88	.....	19.6	8.62	7.38	6.46	10.02	7.00	18.01	12.09	.....	5.95	8.90	3.40	.....	.....	.20
Ol	1.95	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Mt	3.71	.....	5.57	4.41	.....	4.41	.70	5.57	4.87	6.73	3.94	4.18	7.19	7.19	6.73	.....	9.98	6.73	5.57	.....	.....	.....
Il	5.47	.....	5.02	2.58	.....	2.58	.46	6.69	4.10	4.10	3.04	2.89	3.65	4.26	3.04	.....	2.74	3.04	3.04	.....	.....	.30
Hm	.....	.....	.....	.....	.....	.....	2.08	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	5.60	.....	.....	5.28
Ap	1.34	.....	2.35	1.01	.....	1.01	.....	1.68	1.68	1.01	1.01	1.01	1.68	1.34	1.01	.....	1.01	1.34	1.34	.....	.....	.....
C	.....	.....	2.14	.....	.....	.71	.92	1.00	.....	.....	.....	.....	3.37	.....	.....	.....	.....	2.75	.82	.....	.....	.51

Endion Sill

1. Ophitic diabase, shore of Lake Superior at the foot of 18th Ave. E., Duluth. 210 feet above base of sill. S. S. Goldich, analyst.

2. Diabase, shore of Lake Superior at foot of 19th Ave. E., Duluth. 420 feet above base of sill. R. W. Perlich, analyst.

3. Diabase at the first sign of gradation to red rock. Shore of Lake Superior opposite 22d Ave. E., Duluth. 900 feet above base of sill. R. W. Perlich, analyst.

4. Intermediate red rock, McLean quarry near the shore of Lake Superior between 24th and 25th Avenues E., Duluth. 1190 feet above base of sill. R. W. Perlich, analyst.

5. Red rock a few feet from the contact with rhyolite, shore of Lake Superior opposite 27th Ave. E., Duluth. R. W. Perlich, analyst.

6. Red rock within a few feet of contact with rhyolite. Tischer's (Congdon) Creek near 2d St. E., Duluth. R. W. Perlich, analyst.

7. Rhyolite, 50 feet downstream from No. 6. Tischer's (Congdon) Creek near 2d St. E., Duluth. S. S. Goldich, analyst.

Northland Sill

8. Diabase, shore of Lake Superior, at the foot of 30th Ave. E., Duluth. S. S. Goldich, analyst.

9. Reddish diabase, Lester River, NW¼, SW¼, Sec. 32, T. 51 N., R. 13 W. S. S. Goldich, analyst.

10. Red rock, Skyline Boulevard and 41st Ave. projected, Duluth. S. S. Goldich, analyst.

11. Intermediate variety of red rock, Lester River, a quarter of a mile west of the center of Sec. 33, T. 51 N., R. 15 W. R. W. Perlich, analyst.

12. Red rock, Lester River above bridge at Maxwell Road, SW¼, NE¼, Sec. 32, T. 51 N., R. 13 W. S. S. Goldich, analyst.

Lester River Sill

13. Massive, dark, medium-grained diabase. Highway 61, near shore, 1000 feet east of the Lester River bridge, Duluth. 175 feet above base of sill. S. S. Goldich, analyst.

14. Dark, massive diabase. Highway 61, 2000 feet northeast of the Lester River bridge, Duluth. 200 feet above base of sill. L. A. Danielson, analyst.

15. Diabase where red stringers first become abundant, 4600 feet east of the Lester River bridge on the shore of Lake Superior, SW¼, NE¼, Sec. 4, T. 50 N., R. 13 W. 746 feet above base of sill. S. S. Goldich, analyst.

16. Red rock of irregular segregations which grade to diabase. Shore of Lake Superior, SW¼, NE¼, Sec. 4, T. 50 N., R. 13 W. Near No. 15. S. S. Goldich, analyst.

17. Main facies of red rock. Shore of Lake Superior, SE¼, NE¼, Sec. 4, T. 50 N., R. 13 W. 825 feet above base of sill. S. S. Goldich, analyst.

18. Reddish diabase in which No. 19 occurs. Shore of Lake Superior, NE¼, NE¼, Sec. 4, T. 50 N., R. 13 W. 928 feet above base of sill. S. S. Goldich, analyst.

19. Red rock along fractures in No. 18. Same location as No. 18. S. S. Goldich, analyst.

20. Greenish red rock remnant in No. 21. Shore of Lake Superior, NE¼, NE¼, Sec. 4, T. 50 N., R. 13 W. 928 feet above base of sill. S. S. Goldich, analyst.

21. Red alteration of No. 20. Same location as No. 20. S. S. Goldich, analyst.

22. Rhyolite above Lester River sill. Mouth of creek on shore of Lake Superior, NE¼, NE¼, Sec. 34, T. 50 N., R. 13 W. R. W. Perlich, analyst.

of the sill and the intruded rock above. These samples were studied under the microscope and portions were analyzed in the Rock Analysis Laboratory at the University of Minnesota. For the convenience of those interested in technical details the analyses are given in the accompanying table. They were first published in the paper cited at the beginning of this chapter.

The Endion and Lester River sills have rhyolite flows at their upper contacts, so the possibility of contamination being responsible for the granite tops must be considered. Some metamorphism of rhyolite to resemble intrusive granite is fairly clear, but there is no direct evidence of large-scale contribution. Elsewhere in Minnesota, gabbro and diabase with red granite tops occur where no acidic material is available to contaminate the basic magma.

FIGURE 18. — Fond du Lac sandstone, St. Louis River, Sec. 6, T. 48 N., R. 16 W.

FOND DU LAC BEDS

The Fond du Lac beds — often referred to as the Fond du Lac Sandstone — are named from an extensive series of exposures of Upper Keweenawan sedimentary rocks in the St. Louis River valley near the village of Fond du Lac, which is now within the corporate limits of Duluth (Figures 18 and 19). The name of Red Clastic beds was also applied to these exposures, in common with a series of red sandstone and shales found in deep wells in southern Minnesota. Similar rocks crop out near Mora.

In later years Thwaites correlated these exposures with others along the south shore of Lake Superior called the Oronto series.[29] Later, At-

[29] *Sandstones of the Wisconsin Coast of Lake Superior* (Wisconsin Geological and Natural History Survey Bulletin 25, 1912).

water and Clement classified the beds definitely as Amnicon, the upper part of the Oronto series.[30] Still later, Tyler, Marsden, Grout, and Thiel decided on the basis of accessory-mineral studies that the Fond du Lac beds represent the lower part of the Orienta.[31] The difficulty of correlating these sedimentary beds arises from their isolation from beds supposed to be equivalent elsewhere in Minnesota and Wisconsin.

The Fond du Lac beds in the Duluth area are exposed only along the St. Louis River valley in the vicinity of Fond du Lac. The most extensive exposures are along the bluffs overlooking the river from the upper end of the village to the dam about a mile upstream. The best exposures occur along both sides of the river just below the dam in Sec. 6, T. 48 N., R. 15 W. These are partly in Wisconsin because the north-south boundary between the states intersects the river near the south line of the southwest quarter of Sec. 6.

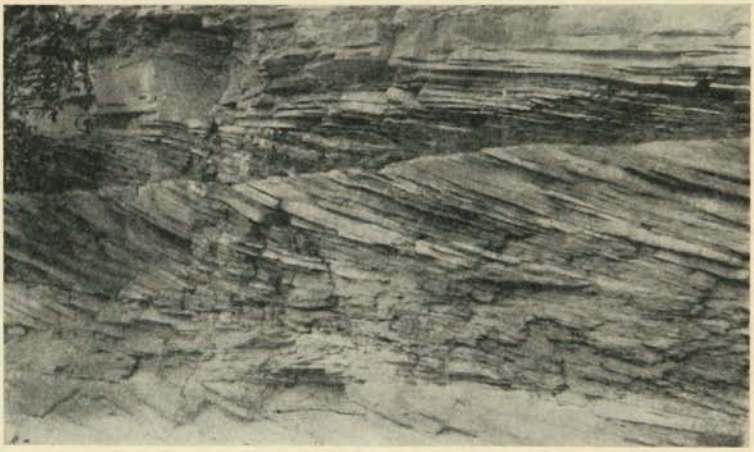

FIGURE 19. — Cross-bedding in Fond du Lac sandstone. Same location as Figure 16.

Some former exposures are now hidden by the pool, but a small exposure of red conglomeratic sandstone, along Little Creek in Sec. 1, T. 48 N., R. 6 W., resembles the Fond du Lac. A little farther upstream the creek bed exposes a quartz pebble conglomerate, presumably Puckwunge, very close to Thomson slate. The exact relations are indeterminate, but if the sandy beds are Fond du Lac a tremendous time interval is represented between them and the Puckwunge. During this interval the thousands of feet of flows and the gabbro at Duluth were formed, as well as

[30] "Pre-Cambrian and Cambrian Relations in the Upper Mississippi Valley," *Bulletin of the Geological Society of America*, 48: 1673–74 (1935).

[31] "Studies of the Lake Superior Pre-Cambrian by the Accessory-mineral Method," *Bulletin of the Geological Society of America*, 51: 1514 (1940).

much of the lower sandstones of the Lake Superior series on the south shore in Wisconsin.

The Fond du Lac beds are extremely variable. Locally they are a fairly massive, medium- to coarse-grained red sandstone, like that which is quarried to a considerable extent. Other beds vary from shaly sandstone to sandy shale and nearly pure shale. These beds lens out rather abruptly as is shown in a road cut along Mission Creek in the NW¼, Sec. 5, T. 48 N., R. 15 W. The sandstones are much cross-bedded and ripple marks are common along bedding planes (Figure 19). The beds are mainly red but vary to gray. At places the red sandstone has small, round, bleached spots where the ferric iron has been reduced. Locally the beds are conglomeratic. Mica is abundant and a variety of pebbles may be recognized, such as shale, quartz, chert, jasper, quartzite, sandstone, porphyry, rhyolite, granite, and basalt. The coarse sandy matrix is feldspathic.

The thickness of the Fond du Lac beds in the area is unknown, since no formation except Pleistocene deposits occur above and the base is not exposed, although the much older slates are very close on Little Creek. C. R. Stauffer measured the section downstream from the powerhouse and obtained a total of 235 feet, as shown in the accompanying table. Drilling for the foundation of the dam showed 75 feet of additional sandy shale and sandstone beds.

Section along St. Louis River, Downstream from Powerhouse
(Measured by C. R. Stauffer)

	THICKNESS (feet)
5. Drift, red clay and stony gray	150
FOND DU LAC BEDS	
4. Sandstone, gray streaked with red, medium to coarse, arkosic, thin- to massive-bedded, ripple-marked	75
3. Shale, red to chocolate, often mottled or streaked with gray. Although argillaceous, it may be arenaceous, ripple-marked and mud-cracked	25
2. Sandstone, red to gray, arkosic, fairly massive, although grading into thin-bedded, gray-spotted, cross-bedded, and micaceous	60
1. Shale, red to chocolate, sandy; shaly sandstone, grading into the sandstone above. The shales are gray-streaked and micaceous and extend to the level of the St. Louis River	75

Similar conglomeratic sandstone was encountered in drilling in the railroad yards at Superior. (See page 124.)

The relation of the Fond du Lac beds to the Middle Keweenawan lava flows and intrusive gabbro and to the Lower Keweenawan Puckwunge sandstone has been referred to briefly. Three possible explanations may be advanced to account for these relations. First, it may be assumed that the flows and gabbro which crop out with a great thickness within 2 miles did not extend as far south as the exposures on Little Creek. This seems highly improbable, in view of the great thickness of flows and intrusives less than 2 miles from the exposures on Mission Creek. The second explanation is based on faulting. This seems the more plausible, but direct evidence of the faults is lacking except for some small faults described by Thwaites. A single great fault such as is often shown along the north shore of Lake Superior cannot account for the exposures along the St. Louis River. A fault parallel to the escarpment in Duluth would pass far to the east of the exposures described. A fault essentially at right angles to the shore of Lake Superior would be required to cut off the flows and gabbro abruptly at the south end of their exposures and permit beds well up from the base of the Upper Keweenawan to occur at Fond du Lac. The third possibility is the existence of an unconformity of considerable proportions between the flows and gabbro and the Fond du Lac beds. Extensive erosion of the flows and gabbro would have permitted the deposition of sediments on the south slope of the igneous rocks as they exist at Ely's Peak. Direct evidence of such an extensive unconformity is lacking.

Pleistocene Deposits

Events of the Pleistocene or glacial period had a profound effect on the Duluth area, and many important aspects of glaciation by the Superior lobe are shown within the area. Winchell pioneered in this work and his results are given in some detail in *The Geology of Minnesota*. Leverett and Sardeson have carried on extensive investigations in Minnesota and over the Superior region and have published the reports found in the chronological list. During the present work, notes on the glacial deposits have been compiled for all the area covered in detail, but in much of the heavily brush-covered areas adequate detail is difficult to obtain. The general topography can scarcely be seen, and the nature of the drift is obscured by vegetation. For these reasons, adequate knowledge of the detailed glacial geology can be obtained only by an expenditure of time and effort out of proportion to the results. The glacial deposits will therefore be treated in a somewhat generalized fashion, with reference to specific details where these are well shown and are of more than passing interest.

The Duluth region was doubtless subjected to repeated glaciation as the various ice sheets crept down from the north. The Superior basin formed a natural location for the formation of a lobe of ice projecting out beyond the ice front on either side. The last extensive invasion was the Superior lobe of late Wisconsin time, which coincided in a general way with the Lake Wisconsin Keewatin ice invasion resulting in the Des Moines lobe of central Minnesota. The scouring and deposition of drift by the Superior lobe practically obliterated evidences of the earlier glaciation so that this description deals almost entirely with the results of the invasion and retreat of the late Wisconsin Superior lobe. The types of deposit left by the Superior lobe and the waters ponded during its retreat are varied. Along the margin of the lobe where the ice front was stationary for a long time, great masses of debris were heaped up to form terminal moraines. Where the ice melted more rapidly, stony but somewhat less hilly areas of ground moraine were formed. The waters pouring from the ice front spread out a nearly level layer of sand and gravel at places to form outwash plains. The area west of Cloquet including the University of Minnesota Experimental Forest is a good example (Plate 4).

Locally rivers beneath the ice filled a channel with stratified sand and gravel that now form long winding ridges known as eskers.

As the ice retreated a great lake formed, and within this great body of water extensive sediments were deposited and shore features developed as much as 500 feet above the present level of Lake Superior. Where streams poured into this lake at its various stages alluvial fans or deltas of stratified sand and gravel were formed. Farther out in the lake the sediment was composed principally of clay.

Lesser lakes were also formed in front of the ice at various places and rather level plains developed when they were drained by retreat of the ice.

GLACIAL LAKE DULUTH AND ITS DEPOSITS

When the ice of the Superior lobe melted back to the Superior basin, water ponded in front of the ice until it overflowed into the headwaters of the St. Croix drainage system. In the early stages, when the water was ponded at its greatest height, the glacial lake extended southwestward to Moose Lake where it overflowed into the Kettle River and thence into the St. Croix (Figure 1).

At one of its highest stages the glacial lake also overflowed at Carlton along a well-defined channel that extends southwestward past Atkinson and Mahtowa to join the Moose River near Barnum (Plates 6 and 7). This occurred perhaps just before the drainage was established at Moose Lake.

A somewhat lower outlet is located farther south in T. 46 N., R. 18 W. but glacial Lake Duluth drained throughout most of its existence by way of the Brule Valley to the headwaters of the St. Croix River in Wisconsin.

The lake which was formed in front of the Superior lobe existed for a considerable period and water was furnished in abundance by the melting ice and by precipitation on the adjacent land. Vegetation was perhaps slow to establish itself on the rock debris left by the retreating glacier, so in the absence of this cover, erosion was rapid. These factors resulted in much sediment being contributed to the lake, and the clays particularly were deposited over all portions of the bottom (Figure 20). The greater portion of the area formerly covered by the various stages of the glacial lake has, therefore, a red clay soil that is largely classified in soil mapping as Superior clay. The deposit varies from clay to silt. Other soil types are loam, sandy loam, and sand. The red clay usually forms a heavy soil; it is compact and absorbs water to become plastic and sticky. It often contains calcareous nodules or concretions. Erratic pebbles are common in some areas but not abundant. At places, such as at Wrenshall (Sec. 28,

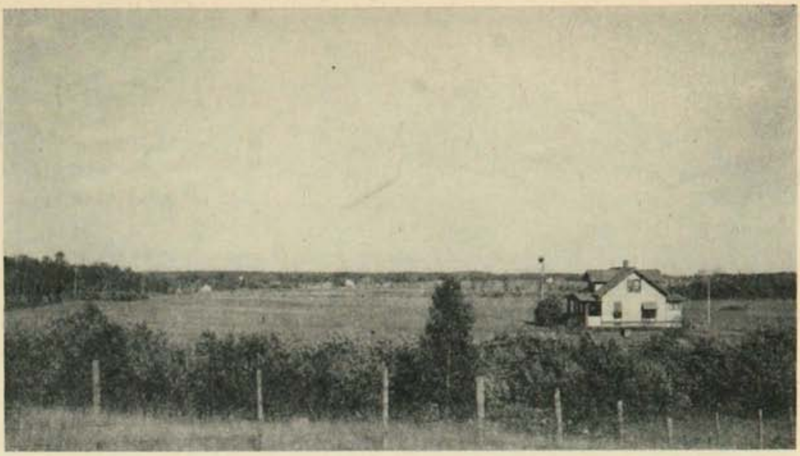

FIGURE 20. — Glacial lake clay plain. Just below the highest beach level of glacial Lake Duluth. Sec. 31, T. 52 N., R. 12 W.

FIGURE 21. — Gravel of the highest beach of glacial Lake Duluth. Sec. 4, T. 51 N., R. 13 W.

T. 48 N., R. 16 W.), the clays are beautifully varved, that is, they are banded. Each narrow band probably represents a seasonal variation and a pair of bands represents a year. The red color is usually confined to the upper few feet and passes into gray below, where oxidation has not been active.

Alongshore, where the lake level was stationary for a considerable time, more or less well-defined beaches were developed. Where steep rock outcrops exist, the beach line may be represented by a wave-cut cliff.

FIGURE 22. — Alluvial fan deposited in glacial Lake Duluth. Shows bottom set, foreset, and topset beds. Sec. 9, T. 51 N., R. 13 W.

FIGURE 23. — Gravel, sand, and varved silt in alluvial fan deposit. Same location as Figure 22.

More common is a ridge of gravel, sand, and boulders (Figure 21). Between the ridges of successive beaches the slopes have often been washed free of fine material, leaving an accumulation of coarse gravel and boulders. At places streams pouring into the lake have left large stratified deposits of sand and gravel, in reality, small deltas (Figures 22, 23).

At Duluth the highest beach is at elevation of 1135 feet (533 feet above Lake Superior); others are at 1110 feet and 1085 feet. The lowest beach is the best developed. It is followed in a general way by Skyline

Parkway above the principal section of the city. The general location of the highest beach level is shown on Plates 8 and 11.

Remnants of other beaches occur on the hillside at Duluth, but most are difficult if not impossible to trace — especially since the growth of the city has greatly disturbed them. The most prominent is referred to the shoreline of glacial Lake Algonquin and occurs at an elevation of 880 feet or about 180 feet above the present lake level.

TERMINAL MORAINES

The terminal moraines of the Superior lobe have been outlined by Leverett on Plate 1 of United States Geological Survey Professional Paper 154. A considerable portion of the Duluth metropolitan area is underlain by a part of the Highland moraine (Plate 4). This moraine marks the northwest border of the Superior lobe from Cook County to Cloquet. Southwest of the St. Louis River the Highland splits into a series of moraines that curve around the southwest end of the Superior lobe, marking various stages of its retreat into the present site of Lake Superior. The moraines falling within the area under consideration are termed the Cloquet, Thomson, Fond du Lac, and the Highland.

Where best developed the morainic belts have a strong knob-and-kettle type of topography with undrained depressions occupied by small lakes or swamps (Figures 2, 24). In general, the moraines are composed of bouldery material with more or less fine material intermixed (Figures 25, 26, 27).

Throughout much of the area the moraines are irregularly developed and it is difficult tc trace a continuous belt. This suggests that the front of the Superior lobe did not remain stationary long enough to heap up a really continuous moraine. Probably the ice was rather thin along the northwest margin owing to the high ridge separating this portion of the glacier from the much thicker main mass in the basin proper.

The areas of terminal moraine merge imperceptibly into areas of glacial drift with comparatively little relief and a rolling topography referred to as till planes or ground moraine (Figure 27). In many areas the distinction between the two is not great, and areas may be differently mapped by different individuals. In general it was found in the detailed work for this report that the total area classified as terminal moraine (Plate 4) was only about half as great as that shown by Leverett and Sardeson's map. The Highland moraine therefore is poorly developed over much of its extent in the Duluth area.

It will be most convenient to describe the ground and terminal moraine belts or areas beginning at the northeast. Tps. 52 N., R. 11 W. and 51 N., R. 12 W. are entirely covered by glacial Lake Duluth sediments and therefore no morainal deposits are exposed. Such as may have existed are buried by glacial lake clays. The northwest portion of T. 52 N., R. 12 W., was not covered by the lake but has only insignificant patches of termi-

FIGURE 24. — Typical shore line of a lake on the Superior upland, Duluth area. Forest consists of white pine, balsam, spruce, poplar, and aspen.

FIGURE 25. — Boulder till of the Highland terminal moraine, Sec. 21, T. 52 N., R. 13 W.

nal moraine, the remainder being underlain by ground moraine with a gently rolling topography and a boulderly soil.

Tps. 51 and 52 N., R. 13 W., however, have a large area of terminal moraine of irregular outline with correspondingly irregular patches of ground moraine. At places the knob-and-sag topography is well developed and the soil is gravelly. In the western portion of these townships the moraine divides and the southern branch trends southwest roughly parallel to the coast. The northern branch trends about due west across

Ranges 14 and 15. Between the branches is a large area of ground moraine centering around Wild Rice Lake and southwestward across T. 50 N., R. 15 W.

The south branch is rather narrow across Tps. 50 and 51 N., R. 14 W., and then widens out on the upland above Duluth. Westward to and beyond Cloquet (Sec. 23, T. 49 N., R. 17 W.), the moraine becomes irregular and is distributed as patches on both sides of the St. Louis River. South of Carlton, about half of Sec. 12, T. 48 N., R. 17 W., has a well-developed moraine which is a portion of the Thomson moraine of Leverett.

FIGURE 26. — Large glacial boulder, Central Park, Duluth.

FIGURE 27. — Boulders in an area of ground moraine deposited by the Superior lobe.

This is separated from the southwest end of the Highland moraine by the wide excavation of the St. Louis River valley. Leverett shows a narrow tongue of moraine southwest of Cloquet and the St. Louis River, which he named the Cloquet moraine. Detailed mapping indicates that this is a series of isolated patches of low moraine surrounded by outwash, and it is doubtful if it deserves a separate name. It is a series of outliers of the Highland moraine.

GROUND MORAINES

The areas of ground moraine are shown in Plate 4 and they need not be described in detail. In general they are gently rolling with abundant boulders in the soil which are often greatly concentrated at the surface (Figures 25, 27). The ground moraine areas are irregular in outline and often contain small patches of weak terminal moraine. At other places the ground moraine occurs as patches in the large terminal moraine areas. As a rule, the soil of the ground moraine has sufficient clay with sand, gravel, and boulders to make it fairly satisfactory for cultivation, except for the never-ending difficulty with boulders. Some areas have too many boulders to make clearing the land worthwhile. Careful investigation of land which it is proposed to clear would seem desirable.

Swamps are fairly abundant in the ground moraine areas and as a rule may not be drained with good results. Locally the ground moraine lies as a very thin cover over the rock surface and difficulty sometimes arises in getting a satisfactory water supply for homes. This is covered in more detail on pages 121–27.

OUTWASH

One of the rather surprising facts about the deposits of the Superior lobe in the Duluth area is the small amount of outwash deposits. Leverett shows only the area west and southwest of Cloquet and Carlton (Tps. 48 and 49 N., R. 17 W.). As might be expected, detailed mapping shows that there are small areas associated with the moraines — for example, at the east end of Pike Lake (Secs. 29 and 31, T. 51 N., R. 15 W.). To the northeast beyond the area described in this report, there are extensive outwash deposits along the northwest border of the Highland moraine.

The main area of outwash west of Cloquet is level to gently rolling, suggesting a morainal deposit buried by the outwash. The elevation varies from 1200 to 1300 feet. Most of the material is sandy, and the soils are mainly sand and fine sandy loam. South of Cloquet to Atkinson some of the soil is a gravelly, sandy loam. Swampy areas with peat soil are fairly extensive, particularly in T. 48 N., R. 17 W. Much of this soil is rather sandy for farming, although it is easy to clear and to work. It once supported an excellent pine forest as is shown by the beautiful remnant now preserved in the Cloquet Forest of the University of Minnesota.

Tps. 51 and 52 N., R. 17 W., were not mapped in detail, but a north-south traverse across the area indicated that considerable areas in these townships shown as ground moraine by Leverett are, in fact, sandy outwash plains with patches of weak terminal moraine. The area west of Grand Lake is a good example.

GLACIAL STRIAE

Many of the rock outcrops of the Duluth area show striae and grooves (Figure 28) resulting from the rock material embedded in the ice scraping over the rocks beneath the ice. In studying the rock exposures, the direction of these striae was recorded as a matter of routine and they are shown on the glacial map (Plate 4).

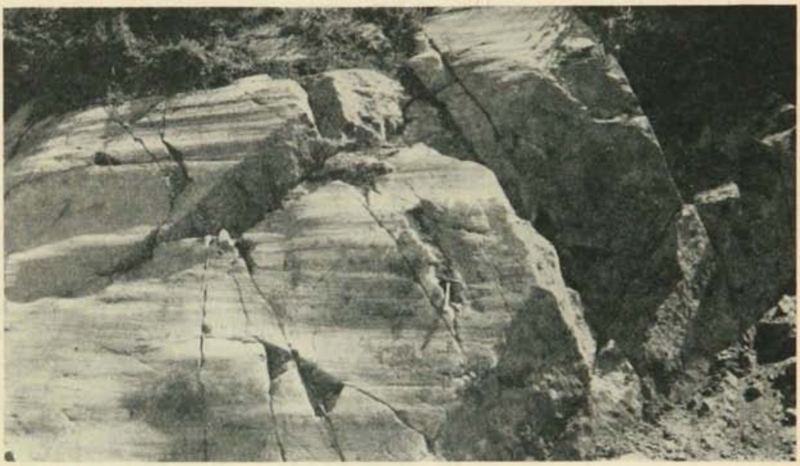

FIGURE 28. — Glacial striae on recently uncovered diabase in road cut. Forest Hill Cemetery, Duluth.

These striae indicate that in the basin of Lake Superior the ice moved essentially parallel to the present shoreline. As the ice moved inland up and over the steep slopes and bluffs, the direction of movement was deflected so that the ice fanned out, and at a distance of a few miles from the present shoreline it moved at about right angles to its direction of movement within the basin. This suggests that the main supply of ice at the southwest end of the Superior lobe came from within the basin and spread laterally from it as well as pushing forward. The front of the ice lobe extended almost to Mille Lacs Lake when forward motion ceased.

SOURCE OF THE GLACIAL DEPOSITS

The Duluth region seemed to offer an opportunity to determine in some measure the source rocks from which the morainal material was derived. The general direction of movement of the ice of the Superior lobe has been known for a long time, and the striae, shown in Figure 28, furnish additional detail. The distribution of the rock formations is such that within the area described in this report additional rock types were available as the ice sheet advanced. Thus alongshore northeast of Duluth and for some distance inland, the bedrock consists of Keweenawan lava flows, associated diabase, and red rock intrusives. From the downtown area of the city westward and northward is the great mass of Duluth gabbro. West of Duluth and in the region around Carlton and Cloquet, the bedrock is slate and graywacke.

Pebble counts are often used to check the composition of the glacial drift. The procedure consisted of picking out a convenient number of pebbles as representative as possible and classifying them as to rock type. Because of the importance of boulders in the Duluth area a similar procedure was used on boulder piles. The data for seventy counts is shown in Figure 29 and the location of the samples is shown by numbers in Plate 4. The graph and numbers are arranged in the direction of ice movement, approximately transverse to formation contacts.

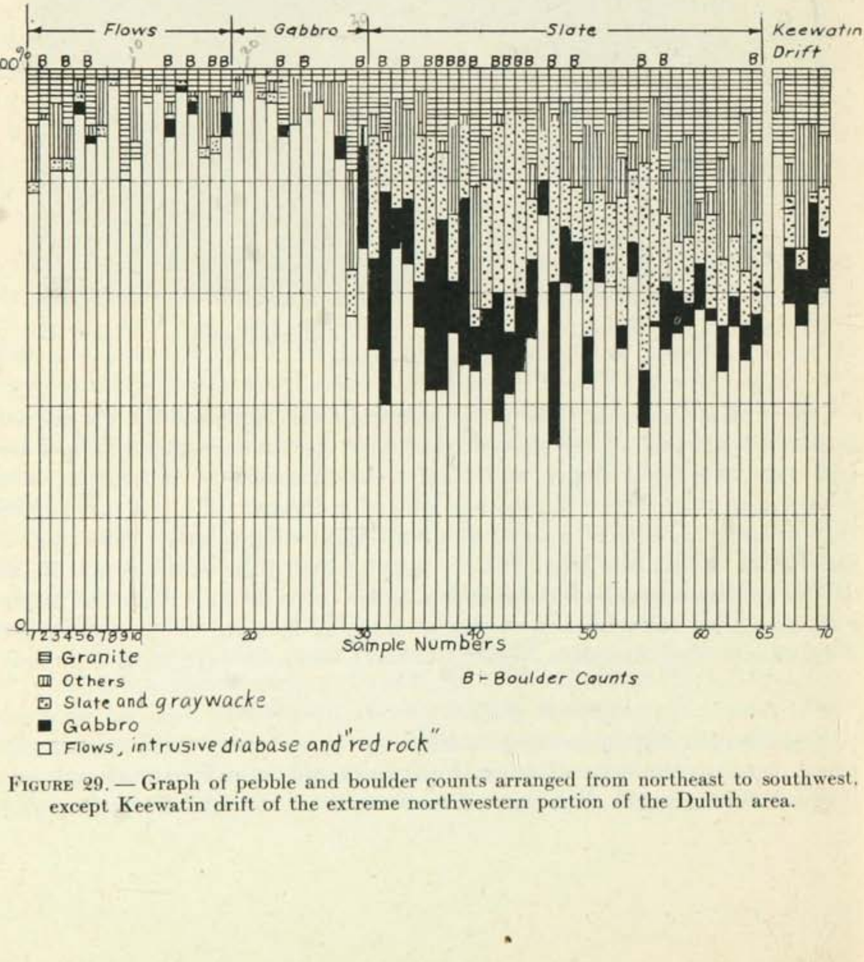

FIGURE 29. — Graph of pebble and boulder counts arranged from northeast to southwest, except Keewatin drift of the extreme northwestern portion of the Duluth area.

The graph brings out several points. There is a relatively high percentage of Keweenawan flow and associated intrusive rocks in the northeast area. This is not surprising in view of the importance of these rocks along both shores of Lake Superior along whose basin the major ice movement was concentrated. Granite is the only other important constituent. This was doubtless carried by the ice from the area northeast of Lake Superior, and the resistance of granite pebbles to abrasion doubtless explains their persistence.

As the ice moved across the Duluth gabbro mass, large amounts of gabbro were incorporated in the ice and deposited in the drift. Unfortunately, there is a gap in the geographic distribution of the counts and none is available for the western portion of the gabbro. The counts in the southwest area, therefore, show a considerable percentage of slate and graywacke. The ice picked up these materials easily from outcrops because of the slaty cleavage. As the ice moved across several miles of gabbro and slate enough gabbro and slate were picked up to constitute about 30 or 40 per cent of the pebbles of the drift. Flows and associated rocks continue to make up roughly 50 per cent even though no new supply was available except a small area of flows at the base of the gabbro in the southern portion of the area.

One rather conspicuous fact is that the percentage of granite is higher in the rocks over the gabbro and slate areas than in the flow area. This is probably a relative matter. That is, granite is resistant, and the pebbles persisted in the ice whereas the flow rocks were more rapidly ground up or decomposed by preglacial weathering to form fine-grained material. Gabbro and slate were probably resistant to plucking by the ice and thus did not contribute as freely to the ice as the flows. Certainly the gabbro is much more massive and resistant than an assemblage of lava flows.

CHAPTER IV

GEOLOGIC STRUCTURE OF THE DULUTH AREA

The general outline of the geologic structure of the Duluth area is determined by its position on the north limb near the west end of the Lake Superior syncline.

The Lake Superior syncline, or geosyncline as it is sometimes called because of its great size, is an enormous boat-shaped depression in the earth's crust. The eastern end of this great downfold is in the Michipicoten area of Ontario somewhat to the north side of the east end of the lake. Westward the axis of the main depression leaves the lake at Ashland, Wisconsin, and extends southwest into Minnesota for a considerable distance before it is lost beneath a cover of Paleozoic rocks and glacial drift.

The syncline is asymmetrical; that is, the dip of the beds on the north side is gentle, averaging perhaps 15°, whereas on the south side Keweenawan beds dip from 35° north to nearly vertical. The Duluth area lying on the north limb, therefore, has rocks with a general low dip toward the Superior basin.

The oldest rock exposed in the area is the Thomson formation. As noted in the description of that formation, its structure is complex and was determined by deformation that antedates Keweenawan time. The Thomson formation is, therefore, in the nature of a basement on which the lower Keweenawan sediments were deposited unconformably. No direct connection between the structure of the Thomson and that of the Superior syncline can be observed.

The Puckwunge conglomerate and sandstone at the extensive exposures in Secs. 17 and 20, T. 49 N., R. 15 W. dips from 10° to 17° in a direction varying from east to south 35° east.

The basalt lava flow overlying the sandstone in Sec. 20 dips about 10° E. The extensive exposures of lava flows that are stratigraphically below the Duluth gabbro at Ely's Peak and elsewhere in the southern portion of T. 49 N., R. 15 W., have dips varying from 9° to 16° in a generally easterly direction but varying considerably at places (Plate 8). Exceptional dips of 30° and 55° were also noted. No doubt metamorphism and disturbance by the intruding gabbro accounts for the irregularities.

The Duluth gabbro in a general way is concordant with the regional structure above and, in part, below. The base of the gabbro roughly follows the strike of the lava flows beneath; that is, it has a trend nearly north-south. As noted in the description of the gabbro it is distinctly banded or layered over a large area. The banding has a fair general uniformity although locally it may be highly irregular (Figure 17). It is safe to say that the average banding is a good index to the general structure of the gabbro mass. The best exposures of the gabbro in the Duluth area are at its extreme southern end at Bardon's Peak. The banding is conspicuous and dips generally from 15° to 30° E.; occasional dips as high as 40° were noted. Wherever the banding is visible throughout the area, this situation holds. Grout estimated the average dip at the south end of the gabbro mass to be about 25°.[1] The lava flows make up the greater portion of the rocks above the gabbro from Mesaba Avenue in Duluth to the northeast beyond the area described in this report. Owing to the crescent-shaped distribution of the flows and the Duluth gabbro on the north shore of Lake Superior, the strike of the lava flows trends inland at Duluth with the lake shore cutting diagonally across successive flows. The top of the gabbro from Mesaba Avenue and Superior Street follows an irregular course but averages nearly due north up to Villa Scholastica, a distance of nearly 3 miles. Beyond, it trends irregularly north-northeast. The average strike from Villa Scholastica to Sec. 1, T. 52 N., R. 13 W., is N. 30° E. It is evident from the irregularity that the top of the gabbro transgresses the flows somewhat.

From Duluth northeastward the average strike of the lava flows swings gradually eastward. In the sewer tunnel beneath Superior Street near Third Avenue West, the strike is about due north-south; at Lester River, N. 18° E.; at Knife River, N. 22° E.; and at Two Harbors, N. 50° E. (Plates 11, 13, 17).

The diabase intrusives in the flows above the gabbro vary from rather diagrammatic sills to irregular intrusives. The Northland sill particularly is irregular. However, the general structure parallels that of the flows so that the Lester River sill, for example, trends more and more easterly from the shore inland to the north line of T. 52 N. (Plate 18).

A few basalt dikes cut the lava flows, but these are usually small and have little importance in the general structure.

It has been generally assumed that the north shore of Lake Superior and the rock bluff overlooking the St. Louis River is a fault scarp. There is no direct evidence of the existence of the fault. The bluff, if it has any relation to a fault has retreated far from the fault line. At Lincoln Park, for example, gabbro is exposed on the flood plain near the St. Louis River 4000 feet from the outcrop at the foot of the bluff. The abruptness with which the gabbro ends to the south does suggest the existence of a fault that cuts off the continuation of the gabbro mass along the projection of the strike of its internal structure as well as the strike of its basal contact with the flows. Other peculiar features of the distribution of formations south of Duluth may be partly explained by faulting.

[1] "Internal Structures of Igneous Rocks," *Journal of Geology*, Vol. 26, Fig. 6 (1918).

CHAPTER V

ORIGIN OF LAKE SUPERIOR

Lake Superior is the largest body of fresh water in the world and also one of the deepest. The term *Superior,* referring to its position as the upper lake of the five Great Lakes of North America, was first used, according to Grace Lee Nute, in the *Jesuit Relation* of 1647–48.[1] The lake is 360 miles long and has a maximum width of 160 miles with an area of about 32,000 square miles. Its normal surface level is 602 feet above sea level, and the greatest official sounding is 217 fathoms (1302 feet) by the Canadian Hydrographic Service at a point about 13 miles northwest of Caribou Island.

In view of its great size and depth it is natural that there should be much interest in the origin of the lake. In addition to its size, another fact of importance in considering the origin is that the lake is located in the trough of a great syncline or downfold in the rocks. This structure of the rocks certainly has had an important effect on the origin of the lake, but that the downfolding of the rocks is the primary cause of the present lake is doubtful in view of the great length of time since the folding. The folding can be fairly closely dated as late Keweenawan, or some 600,000,000 years ago. This would seem to allow plenty of time for any depression formed by the folding to have been filled with sediments. Another fundamental fact to be considered in the origin of the present lake is the great depth of its bottom below sea level. The depression could, therefore, not have formed by stream erosion unless this whole portion of the continent was once much higher above sea level than it is at present. While there have been changes in both continental and sea levels, there is no good evidence that these were on a scale to account for the Superior depression.

There are two main possible explanations: (1) The lake was scoured out by successive ice lobes which probably occupied the rock basin culminating in the Superior lobe of late Wisconsin time. (2) Depression of the basin was caused by faulting at a sufficiently late date for it to have escaped filling with sediment.

Difficulties with the fault hypothesis are the lack of evidence of late faulting anywhere at this portion of the North American continent and the lack of good evidence of faults in the proper positions to account for the depression. Certain ancient great faults are known to exist in the Superior region, and it is reasonable to assume that their existence has modified the course of erosion, but these faults do not bound the Lake Superior basin.

[1] *Lake Superior,* p. 21 (1944).

The hypothesis of glacial erosion has more obvious support. The movement of the Superior ice lobe down the axis of the lake was one of the last great geologic events in the region. The timing to account for the present depression is excellent. Futhermore, it is evident from the moraines of the Superior lobe, as shown by Leverett's maps, that a great deal of rock debris was picked up by the lobe and deposited to the southwest of the present lake, although some of the latest moraines are within the basin. It is also shown by glacial drift to the southwest in Minnesota that earlier ice sheets passed over the Superior region and gathered up enormous amounts of rock debris, and carried it on to the southwest. It is reasonable to suppose, therefore, that the Superior syncline was occupied by previous lobes that moved along the length of the basin, gouging it out to a greater extent each time it was occupied by a lobe of ice.

In summary it may be said that Lake Superior probably owes its origin to a combination of conditions. The first important event was the formation of the great syncline following the extensive igneous extrusions and intrusions of the Keweenawan. This syncline no doubt was expressed at the surface by a basin that was filled by later and softer rocks than the older rocks around the edges. Faulting at a still later time modified the structure of portions of the syncline. Some of the faulting has been considered of late Keweenawan age; part of the movement is Paleozoic or later. It is generally assumed that a large river valley occupied the present site of the lake and guided the early glacial erosion. The immediate cause of the present topographic basin was deepening by successive lobes of glacial ice that occupied the bottom of the syncline and eroded out the soft sediments but modified only in a moderate degree the resistant pre-Cambrian rocks on the sides.

CHAPTER VI

SUMMARY OF THE GEOLOGICAL HISTORY OF THE DULUTH REGION

In order to appreciate the full geologic history of the Duluth region it is necessary to include events revealed by rocks exposed in adjacent regions as well as those exposed in the area itself.

Keewatin

The Keewatin rocks found in northeastern Minnesota are among the oldest recognized by geologists, and present estimates suggest that these rocks are perhaps 2,000,000,000 years old. In northern St. Louis County the Ely greenstone is the principal Keewatin rock and was formed by a great outburst of volcanic flows and eruptions evidently much like that which formed the later flows exposed at Duluth. These old volcanic rocks are widely exposed in the great area of Canada east of the Rocky Mountains, and this early period of volcanic activity was no doubt one of the greatest in all earth history.

Late in this period of volcanic activity seas covered some of the area at one or more intervals and the jaspilite of the Soudan iron-bearing formation was formed.

Laurentian

Following the formation of the Keewatin volcanic rocks, possibly after a long interval, the region was invaded by large masses of magma which formed the Laurentian granites represented in northeastern Minnesota by the Saganaga and perhaps other granites. The intrusion of the molten material resulted in considerable metamorphism of the preexisting basaltic flows. Following the intrusion of the granites, there was a long period of erosion during which both the flows and the granite were exposed at the surface.

Knife Lake Time

Following erosion there was a period of deposition of sediments, some possibly in the sea, others as delta and river deposits. Conglomerates, graywackes, and slates now represent the original gravels, sand, and muds.

Possibly during this time the sands and muds, now represented by the Thomson formation, were laid down. But there has been considerable argument as to the time of deposition of these sediments, and we may never be certain of their exact correlation. The evidence now available suggests their deposition at a relatively early date and their subsequent deformation and metamorphism.

Algoman

Farther north in the vicinity of the Mesabi range and still farther north in St. Louis County is a series of granite intrusions younger than the sediments noted above but older than the rocks of the Mesabi range proper. There was again a long period of erosion after the intrusion of the granites; then the formations of the Mesabi range were laid down. A period of deformation of varying intensity affected these rocks. In general, the deformation was slight on the north side of Lake Superior and severe on the south side. Available evidence indicates that the Virginia slate of the Mesabi range is younger than the Thomson slates and graywackes.

In any event along the lower St. Louis River the slates and graywackes of the Thomson formation are severely folded, and lying on their eroded edges are conglomerates and sandstone of early Keweenawan time, thus forming a pronounced unconformity.

Keweenawan

Apparently the period of sedimentation of early Keweenawan was of short duration, at least in the Duluth region, for the sediments do not exceed 200 feet in thickness. There is a suggestion in the Short Line Park well that the sandstone and flows are interbedded.

The sedimentation was largely ended by a tremendous outburst of volcanic activity over large parts of the Lake Superior district, extending southward at least as far as Stillwater, Minnesota. The flows evidently came from great fissures, probably from areas now beneath Lake Superior. Most of the flows were of dark basaltic material, but at intervals considerable thicknesses of red felsitic flows were formed and are now interbedded with the basalts. Occasionally there was time enough between flows for thin beds of sediments to form or fill cracks in the flows.

The enormous thickness of these flows and their great number are almost unbelievable. A. E. Sandberg spent many months methodically counting and measuring all the flows exposed from their base near Nopeming to Two Harbors and gives the number as well over two hundred. Some are covered and the exact number cannot be determined. The thickness was measured as 20,806 feet, which includes 267 feet of interflow fragmental rocks. Other flows along the coast to the northeast lie above this series.

After the lava flows had been poured out in great thickness, the molten material continued to work its way upward. At places it could not reach the surface but instead forced its way between and across the flows and other rocks, forming a great number of dikes, sills, and largest and most important of all, the huge mass of the Duluth gabbro lopolith. It is not likely that these intrusions all formed at the same time, but they form such a complicated series that it seems impossible to work out any definite sequence.

It probably took the Duluth gabbro thousands of years to cool, during which it segregated into layers of varied composition, but the main portion consists of several varieties of gabbro and a thin upper and lighter portion of red rock (granite).

Finally this long period of igneous activity came to a close and once again gravels and sands were deposited, forming the Upper Keweenawan sandstone beds now exposed along the St. Louis River at Fond du Lac.

From the end of the time of the deposition of the sands of the Upper Keweenawan for a period of hundreds of years, there is no record of events in the Duluth region, although we know that a large thickness of sediments was deposited farther south in the Mississippi valley area. It is a reasonable assumption that during much of this time the Superior area was subject to more or less erosion.

Pleistocene

The next events to leave a definite record in the Duluth area are those of the Pleistocene or glacial period. It is reasonably certain that several glaciers passed over the region. Probably scouring by successive lobes of these glaciers is responsible for the huge basin of Lake Superior, which extends hundreds of feet below sea level at places. The glacier on melting formed extensive deposits such as terminal and ground moraines, outwash plains, and the glacial lake sediments. As the front of the Superior lobe retreated, the natural drainage to the St. Lawrence was still blocked by ice, so the waters ponded in front of the glacier until they could overflow into the St. Croix River basin. The beaches and deposits within the basin formed many present features of the area.

Stream erosion has only slightly modified most of the area since the disappearance of the Superior lobe; however, the glacial lake clay plain along the lower St. Louis River has been considerably dissected by short tributaries which have a fairly steep gradient.

Tilting of the area following the disappearance of the glacier ponded the water at the southeast end of Lake Superior to form the harbor.

CHAPTER VII

GEOLOGY OF THE CITY OF DULUTH

The city of Duluth is strung out along the north side of the St. Louis River and of Lake Superior for a distance of 26 miles. Throughout much of this area outcrops are abundant, and it is difficult to describe the geology in an intelligible manner. The geology of the main portion of the city is shown on Plate 11.[1] Smaller portions are shown on Plates 5, 8, 14, and 15. Accordingly, the main outlines will be described first, then important or interesting features will be taken up as systematically as possible.

There are two principal subdivisions of the bedrock geology of the city. From Mesaba Avenue westward the outcrops are of various phases of the Duluth gabbro intrusive. East of Mesaba Avenue the rocks consist of a thick series of lava flows in which a series of diabase sills, dikes, and irregular bodies have been intruded.

At the extreme southwest end of the city, in the suburb of Fond du Lac, is a limited area of Upper Keweenawan sediments. Along the north side of the St. Louis River, from Rice's Point westward, is a narrow plain which has a thick deposit of glacial till with a thin surface deposit of glacial lake sediments and, nearest the river, probably alluvial deposits. With one or two exceptions outcrops do not occur in this area, and little is known about the bedrock underlying the surficial deposits.

Gabbro is a massive igneous rock. Because it is resistant to weathering in a cool climate, this igneous rock tends to form high, broad ridges. This is well shown in Duluth, where massive hills face the St. Louis River and Lake Superior from Bardon's Peak near the west end of Duluth to Mesaba Avenue, where the highest ridge trends somewhat inland with the top of the gabbro. The hard hornfels zone occurs directly above the ridge.

The base of the gabbro is poorly exposed even in this area of abundant outcrops. The best place to see the contact is on the Canadian National Railway along a small creek valley in Sec. 33, T. 49 N., R. 15 W., which is just north of the city limits (Plate 8). Here flow-hornfels are exposed with red pegmatites just below coarse gabbro.

Bardon's Peak in Sec. 34, just west of the Minnesota Steel Company plant, is a high, dome-like mass of gabbro consisting principally of well-banded troctolite, which is a rock consisting mainly of plagioclase, feldspar, and olivine. The bands have a somewhat variable dip and strike, but on the average they strike west of north and dip from 20° to 45°.

[1] In using the maps in this report it will be convenient to have available a city map which shows the street names.

An average of seventeen readings in Secs. 33 and 34 gave a dip of 31°. The most southerly outcrop of gabbro occurs just south of the Northern Pacific Railway in Sec. 3, T. 48 N., R. 15 W., along a small creek. How much farther the gabbro extends is a matter of guesswork because the thick surficial deposits of the St. Louis valley and the basin of Lake Duluth mask everything.

Two hundred and fifty paces north of the same tracks in Sec. 34 and fifty paces west of the west forty line is an outcrop of banded gabbro which has close-spaced jointing with the attitude at an angle to the bedding such as is usually characteristic of fracture cleavage. This suggests some movement of the gabbro when it had reached at least a partially solid state.

Outcrops of olivine gabbro are abundant northward in Sec. 27 along the railroads and Skyline Parkway. Banding is conspicuous, and the strike seems to veer somewhat to the east of north with dips of 20° to 30°.

At the base of the bluff in Sec. 34 just north of the cement plant, a ridge of gabbro extends nearly to Highway 23. This is a medium-coarse olivine gabbro and does not show well-defined banding. In other words, banding is more conspicuous westward nearer the base of the gabbro.

Along the boulevard from Bardon's Peak northward is much coarse olivine gabbro with only occasional banding, in contrast to the highly developed banding on the west side of the peak. Near the north side of Sec. 27 Steward Creek follows a prominent shear zone from the boulevard downstream. Slickensides and calcite veins are numerous. The trend is about east-west.

Northward, in Secs. 22 and 23, outcrops become more scattered but are still fairly numerous along the escarpment facing the river. These outcrops are farther from the base of the gabbro and have a lesser dip; the average is about 16°.

Exposures are abundant along Knowlton's Creek in the southeast quarter of Sec. 15 and the southwest quarter of Sec. 14, where the dip of banding is about 20°. Extensive exposures occur at Rest Point on Highway 61 near the center of Sec. 14. The rock here is typical, coarse, olivine gabbro with abundant pyroxene. This is probably the best exposure of the coarsest facies of the banded olivine gabbro. Some portions are massive rather than banded. The first coarse feldspathic gabbro inclusion seen from the base upward is found on Kingsbury Creek just below the bridge on Highway 61. Below the railroad tracks the olivine gabbro is well banded at places.

Along Seventy-seventh Avenue West — that is the line between Secs. 1 and 2, T. 49 N., R. 15 W. — and also southward in Secs. 11 and 12 is a rather coarse, high pyroxene gabbro which under favorable conditions shows an orientation of the feldspars but no apparent banding. Flat surfaces of the outcrops strike about north-south and dip 10° E., which is probably the plane of orientation of the feldspar. There is also more coarse pyroxene than in most of the gabbro along the bluff.

Keene Creek is a small stream which starts in the northern part of Sec. 1, T. 49 N., R. 15 W., and flows south and slightly eastward through Secs. 1 and 12 toward St. Louis Bay. A steep, narrow gorge has been cut in the southwest quarter of Sec. 1 from Oneota Cemetery upstream. The rock exposed is mainly medium-grained, massive gabbro, but locally there are large masses of feldspathic gabbro, probably inclusions. Above the old concrete bridge of Skyline Parkway magnetite is segregated along thin bands. A red rock dike about 8 inches wide cuts the gabbro nearly vertically. At places the banding is irregular and forms swirls, but the more regular bands strike about north and dip 20° E. Good basic pegmatitic segregations occur in the cuts along the boulevard on the west bank. The northern cut is one of the best known exposures to show banded olivine gabbro, coarse feldspathic gabbro with abundant basic pegmatites, and magnetite. Coarse plagioclase and pyroxene occur in the pegmatitic portions. Some of the feldspar is reddened by alteration. Fibrous alteration products also occur. An inclusion of basalt hornfels also occurs at the north end of the exposure. The gabbro is generally complex in this area. Along the power line, near the center of the northeast quarter of Sec. 1, the exposures show a mixture of coarse and medium-grained gabbro with each apparently intruding the other at different places. The normal relation in the Duluth area is the finer grained later than the coarse.

North of the Canadian National shops, mainly in the southwest quarter of Sec. 12, T. 49 N., R. 15 W., is a hillside with many large exposures. These are mixed, coarse, mottled gabbro and medium, even-grained gabbro. Generally banding is not clear and where visible is irregular. Locally the medium-grained facies intrudes and encloses the coarse-grained facies. The bands, when visible, seem to strike northwesterly or at about right angles to normal.

Along Skyline Boulevard in the southeast portion of Sec. 1, T. 49 N., R. 15 W., and extending eastward into Sec. 6, T. 49 N., R. 14 W., is a high sea cliff, the upper beach level of Lake Duluth. The rock here is a confused mixture of very coarse feldspathic gabbro with finer-grained olivine gabbro. Flow stricture is often indicated by oriented lath-shaped feldspar crystals. There is little evidence of the banding which is conspicuous farther west.

At the foot of the bluff east of Keene Creek near Longfellow School is an extensive series of exposures in addition to extremely variable and irregular gabbro, varying both in texture and composition. At the south end of the exposures coarse patches are almost pegmatitic in nature.

The largest and most continuous rock exposures in Duluth occur in an area of perhaps 2 square miles, lying between Brewer Park in the southwest quarter of Sec. 6, T. 49 N., R. 14 W., and Lincoln Park along

Miller's Creek (Plate 11). The belt extends from the tracks of the Duluth, Missabe, and Iron Range Railway to the central part of Sec. 31, T. 50 N., R. 14 W., above Skyline Boulevard.

At Fifty-ninth Avenue West and north of the railroad is a large quarry which exposes a long face of gabbro with hornfels which have rather complicated relations. At the east end very coarse feldspathic gabbro with reddish patches is exposed at the base of the vertical face. Above the feldspathic gabbro there is a 6-foot layer of black hornfels, and above that is a finer-grained diabase gabbro. Along the top of the main face there is generally a zone of finer-grained gabbro, but at places coarse feldspathic gabbro breaks across to form the top of the cliff. The hornfels seems without much doubt to represent large inclusions of basalt in the gabbro which have been completely recrystallized by the heat of the gabbro.

The extensive exposures in the northern part of Sec. 6, T. 49 N., R. 14 W., and in Sec. 31, T. 50 N., R. 14 W., consist mainly of medium-grained, olivine gabbro with numerous large inclusions of feldspathic gabbro.

In Lincoln Park exposures are almost continuous from Third Street to Skyline Boulevard. From Third to Tenth streets there is coarse feldspathic gabbro, the creek following joint planes at places. Above Tenth Street a dense black diabase gabbro occurs with much red rock mixed with it.

The gradational relation of red rock to gabbro is clear, as is the fact that the red rock intrudes feldspathic gabbro. Red stringers with sharply defined walls may be traced into streaks which grade into dark gabbro.

West of Lincoln Park, at the corner of Twenty-seventh Avenue West and Twelfth Street, a rock cut exposes feldspathic gabbro — dense black diabasic gabbro with red rock cutting both gabbro facies. Inclusions of the diabasic facies occur in red rock with both included in the feldspathic facies.

Opposite the areas of extensive outcrops, referred to above, and directly below Lincoln Park an important exposure occurs on the terrace along the St. Louis River. This is located between Twenty-sixth and Twenty-seventh Avenues West along the right-of-way of the Northern Pacific Railway and the Duluth, Missabe, and Iron Range Railway. The exposures consist of coarse feldspathic gabbro with hornfels, inclusions, red rock stringers, a red rock dike, and a dense basalt dike. This is nearly a mile in front of the main bluff of gabbro and proves that the bluff is simply an erosional scarp and not necessarily related to a supposed north shore fault.

Central and Enger parks cover a large area starting at First Street between Fourteenth and Seventeenth Avenues West and continuing up the hillside where Enger Park is a mile long east and west and a half mile wide. Outcrops are almost continuous from the area below Central Park up the hill to the upper branch of Skyline Boulevard. Owing to the relation in and near this area, these outcrops are particularly important in understanding the gabbro mass.

In a general way the exposures west of the parks consist mainly of feldspathic gabbro with relatively insignificant amounts of red rock. In Central Park and eastward, particularly along Buckingham Creek, considerable amounts of red rock occur with the gabbro. The principal red rock area is approximately bounded by Third Street on the south, Seventh Street on the north, Central Park on the west, and Tenth Avenue West.

In Central Park there are many stages of gradation from gabbro to red rock (granophyre). A quarry at Thirteenth Avenue West and Second Street shows red rock later than anorthosite, which is shattered and somewhat assimilated. In Buckingham Creek below Third Street West is a complex of red rock in gabbro along the border of the main red rock area. The border of the red rock area is, in fact, all gradational and irregular so that the contact is more or less hypothetical. Much gabbro has been permeated with granophyre but retains the texture of the feldspathic gabbro. Inclusions of gabbro are abundant wherever red rock becomes dominant.

Just below the boulevard at Fifth Street and Fourteenth Avenue West, red rock has a profusion of lath-shaped plagioclase crystals, much altered to epidote. Probably the crystals are inclusions derived from anorthosite.

At Superior Street and Thirteenth Avenue West is a cliff known as "Point of Rocks." Considerable quarrying for a proposed extension of Superior Street gives large fresh exposures of gabbro. The trunk sewer tunnel passes beneath this area.

The upper contact of the gabbro has not been located south of Superior Street. The gabbro outcrops end just along the east side of Mesaba Avenue at Superior. Just to the east we know the precise location of the contact, thanks to the sewer tunnel. It is midway between Fifth and Sixth Avenues West beneath First Street. Outcrops serve to show the trend of the contact northward fairly closely to Skyline Boulevard. Beyond (northwest of) the boulevard outcrops are abundant up to Thirteenth Street. The contact is winding and not easy to locate in the complex of hornfels and gabbro, but it follows Fourth Avenue West fairly closely to Eleventh Avenue, where the trend changes to nearly due north across the southern part of Sec. 21, T. 50 N., R. 14 W. The exact contact is exposed in an outcrop area in the SE¼, NE¼, Sec. 21. Beyond this, scattered exposures show that the contact is rather irregular but follows roughly along the line between the southern half of Secs. 15 and 16, thence diagonally northeast across Secs. 15 and 10; beyond that it swings east to Forest Hill Cemetery, where it turns north across Sec. 1, T. 50 N., and Sec. 36, T. 51 N., R. 14 W., to the city limits.

As previously noted, the upper portion of the gabbro mass is variable and no general description will necessarily apply to specific outcrops. At places the contact is indefinite, consisting of a zone of mixed hornfels and gabbro. This is well shown along the projection of Fourth Avenue West from Skyline Boulevard northward. Here a rounded hill shows abundant exposures. Some consist of highly recrystallized basalt hornfels permeated by gabbro; others consist of gabbro with abundant inclusions of hornfels. The hornfels presents the characteristic rusty, seamed appearance which makes its recognition easy on weathered surfaces.

Just below Ninth Street in line with Tenth Avenue West is a complex of basalt hornfels with a confusion of red stringers and irregular masses.

North of Thirteenth Street exposures are few along the contact for a mile along the east side of Sec. 21, T. 50 N., R. 14 W. The actual contact is exposed at one place in the section just north of Upham Road.

Exposures are abundant along the line between Secs. 15 and 16 to a point north of the quarter corner. The contact here is irregular and more or less gabbro has permeated the flow hornfels. Hornfels inclusions are numerous in the gabbro. At places a contact can be seen between nearly pure gabbro and hornfels with less than 10 per cent gabbro. The gabbro is a coarse feldspathic type with coarse basic pegmatitic segregations. The quarry back of Villa Scholastica shows excellent porphyrite hornfels and also dense basalt hornfels.

Between Villa Scholastica and the northeast corner of Sec. 10 there are only scattered outcrops of gabbro with one small exposure of the contact on Kenwood Avenue just north of Howard Gniesen Road. West of Hartley Road, in the northeast corner of Sec. 10 and northwest corner of Sec. 11, is a large rock hill with gabbro on the northwest side and basalt on the southeast. Here the contact turns sharply eastward, and at Forest Hill Cemetery the outcrops above the gabbro are diabase. Exposures of diabase are numerous from the cemetery southward to the continuous exposures of the Endion sill on the shore of Lake Superior.

The only other extensive exposures near the top of the gabbro occur along the west branch of Amity Creek in Sec. 1, T. 50 N., R. 14 W., and Sec. 35, T. 51 N., R. 14 W. The exposures are a complex of gabbro and red rock with basic pegmatite segregations in the gabbro. For a considerable distance the creek seems to follow the contact between gabbro on the west and red granite on the east.

East of the gabbro contact in the city the bed rock consists mainly of lava flows intruded by several sills and irregular masses of diabase.

The complete tabulation of the flows with their classification and thickness is given on pages 38–42, and the general features of the intrusives have been covered in pages 52–66. The following comments apply to the important details of exposures east of Mesaba Avenue.

Extensive exposures occur along Chester Creek and particularly southwest of the creek between Skyline Boulevard and Kenwood Avenue and also west of Kenwood Avenue.

The area between Kenwood and the boulevard is a high rounded hill with extensive outcrops of basalt scattered over it. The basalt appears baked and has many red rock stringers. Some of these exposures are nearly a mile from the gabbro contact as now exposed. This is perhaps the greatest distance from the contact that metamorphism has been recognized.

Along Chester Creek between Superior and Second streets there are excellent exposures of an interflow sandstone. It is cross-bedded and dark gray to reddish in color.

Between Chester Creek and Congdon Creek are scattered exposures of diabase except for the complete section of the Endion sill alongshore. Rhyolite occurs alongshore from the upper contact of the Endion sill on shore at Twenty-seventh Avenue East and east to the mouth of Congdon Creek except for a narrow extension of the Northland sill, which recubes the shore opposite Thirtieth Avenue East. The gorge of Congdon Creek gives an excellent cross section of the Northland and much of the Endion sills.

The contact between the rhyolite exposed alongshore and the Northland sill is just above the railroad bridge. Between the bridge and Greysolon Place is a complex of diabase and rhyolite which represents the Northland intrusive. Rhyolite free from diabase extends from Greysolon Place to a point on the creek opposite Second Street, where the red rock of the Endion sill is exposed. The red rock grades through intermediate rock to diabase between Second and Fourth streets. Diabase is continuous to Wallace Avenue; above there the creek seems to have ponded against the diabase, and the creek flows in a shallow valley which has almost been filled with alluvium.

Between Congdon Creek and the Lester River the exposures are confined to the lake shore and to the diabase ridge of the Northland sill, which is a narrow sill on shore opposite Thirtieth Avenue East. This sill becomes wider where it is crossed by Congdon Creek and then widens out greatly as it crosses the grounds of the Country Club. Beyond the Country Club in Sec. 6, T. 50 N., R. 13 W., and in Sec. 32, T. 51 N., R. 13 W., the sill forms a long ridge which is traversed by Skyline Boulevard. Some of the exposures of the sill are complex mixtures of diabase, intermediate rock, and granophyr (red rock). A hill of diabase in the SW½, NW¼, Sec. 6, contains a typical boulder-like mass of pure anorthosite included in the diabase. This is the only example known in the city of the anorthosite masses so common in eastern Lake County near Lake Superior.

Most of the area southeast and east of the Northland sill to the Lester River has a heavy cover of red glacial lake clay. Rock outcrops are largely lacking except alongshore.

The gorges of both the east and west branches of the Lester River are cut into rock along their lower portions. The rocks along both branches are flows except at the center of Sec. 32, T. 51 N., R. 13 W., where the diabase and red rock of the Northland sill form a sharp change in the course of the west branch. Several flows are exposed and some of the features of the tops of flows are well shown. Thin sandstone beds separate some of the flows, and sandstone dikes and narrow basalt dikes may be seen. A felsite flow is well exposed along the east branch. Flow structures are a prominent feature of the felsite.

East of the Lester River the outcrops occur alongshore and inland along the strike of the Lester River diabase sill. The surface of the sill rises gradually from the lake to the hill at the city limits in the northeast corner of Sec. 33, T. 51 N., R. 13 W. Scattered diabase outcrops occur over the low area, but otherwise a heavy cover of red lake clay covers bedrock.

CHAPTER VIII

TOWNSHIP DESCRIPTIONS

Township 48 North, Range 15 West

SURFACE FEATURES

Only the northern portion of this township lies in Minnesota on the north side of the St. Louis River (Plate 5). The greater part of the township lies on the alluvial plain which exists along the river below the Fond du Lac dam. This plain was covered by the waters of glacial Lake Duluth and has a heavy deposit of red lake clay. In Sec. 9 an extensive gravel deposit represents in Sargent's Creek valley a delta deposit of the stream during the glacial period (Figures 22 and 23).

The St. Louis River is ponded up as far as Fond du Lac by the tilting of Lake Superior following the gradual melting of the ice of the Superior lobe. The drowning of the river valley accounts for the width of the river and its irregular area with bays caused by the flooding of depressions along the original course of the stream.

GEOLOGY

This fraction of a township is a significant location in Lake Superior geology. Here in Sec. 4 are the most southerly outcrops of the Keweenawan lava flows which extend along the entire Minnesota coast of Lake Superior. In Sec. 5 also are some of the southernmost outcrops of the great Duluth gabbro mass that forms a large crescent-shaped area north of Lake Superior. In Secs. 5 and 6 are extensive exposures of the Upper Keweenawan shaly sandstone known as the Fond du Lac beds (Figures 18 and 19).

The oldest rocks are the lava flows at the foot of the bluff just east of Short Line Park Station (Figure 14). The railroad cut exposes a rather coarse porphyritic rock which is probably part of a thick lava flow. This and the finer-grained rock to the west have been somewhat recrystallized by their proximity to the gabbro.

Along a small creek in the northwest corner of Sec. 3 are the most southerly outcrops of the Duluth gabbro. What causes the outcrops of both the flows and gabbro to end abruptly is problematical. A fault is commonly assumed to be responsible, but there is no positive evidence of such a fault. Erosion could account for the present situation, although in that case the flows or gabbro should appear somewhere to the south.

To the southwest in Secs. 5 and 6 there are extensive exposures of the Fond du Lac beds along Mission Creek and the St. Louis River. The rock varies from red sandstone to red shale. The sandstone beds are much cross-bedded where the rock is more massive (Figure 19). Many beds are thin and slabby. Locally there are conglomeratic beds with shale pebbles and coarse sand with a variety of other pebbles, including porphyry, chert, rhyolite, jasper, granite, basalt, sandstone, and quartz.

The relation of the Fond du Lac beds to the flows and gabbro is debatable. The Fond du Lac beds have been correlated on the basis of lithology and heavy residuals with the Orienta of Wisconsin. This formation is well up in the Upper Keweenawan sandstone series, so it is probable that either a fault or a big unconformity separates the area of Fond du Lac beds from the flows and gabbro a short distance to the northeast. If a fault accounts for the abrupt termination of the flows and gabbro, it would seem to have a general east-west strike, actually somewhat south of east rather than a northeast strike as the supposed fault along the north shore of Lake Superior must have if it exists.

Township 48 North, Range 16 West

SURFACE FEATURES

The surface of this township shows a considerable variation, and no general characterization can apply to the area as a whole (Plate 6). It will, therefore, be described by areas according to their origin and character.

The most prominent physiographic feature is the St. Louis River, which enters the township near the northeast corner in Sec. 6 and flows somewhat southeasterly to Sec. 15, where it makes an abrupt turn to the northeast and leaves the township in the southeast portion of Sec. 1. South of the St. Louis River the greater part of the township is underlain by the deposits, particularly clays, of Lake Duluth. Some of this lake plain has been extensively eroded.

The extreme western portion of the township, Secs. 17, 18, 19, 20, 30, and 31, consists of rolling to hummocky terminal moraine deposits which rose above the highest level of Lake Duluth. At many places the old shoreline can be easily recognized and has been mapped with greater accuracy than is usual because much of the area has been cleared of brush (Plate 6). The soil in the terminal moraine varies from silty to gravelly. Locally, boulders are abundant. Gravel deposits are numerous, and several have been opened for local use.

The south-central portion of the township, particularly around Wrenshall, is an almost level lake plain, except where streams have entrenched themselves in the easily eroded lake clays. The clay deposits which have been used for a long time are described in Chapter IX. Excellent varves occur in the clay pits at Wrenshall.

Along the St. Louis River from Sec. 9 eastward, and particularly along Silver Creek, a tributary in Secs. 15 and 16, the lake plain has been extensively dissected because of the steep gradient to the St. Louis River. Thus, all or much of Secs. 1, 2, 10, 11, 12, 13, 14, 15, 16, 21, 22, 23, and small portions of some adjacent sections may best be classified as dissected glacial lake plain. Large areas of the plain have been destroyed by gullying. The clays in general are highly plastic and on steep slopes tend to slide easily; consequently scars of recent landslides are a common feature along streams where the toe of the slope is undercut by flood waters.

Much of the southeastern corner of the township, including portions of Secs. 13, 23, 26, 27, and 35 and all of Secs. 24, 25, 35, and 36 are underlain by the Fond du Lac terminal moraine which, according to Leverett, was laid down in the glacial lake ponded in front of the Superior lobe. It is certain that the area was covered by glacial Lake Duluth so that lake clays, some with excellent varves, occur at places. A small portion of the southeast corner, mainly Sec. 36, is more nearly level than areas to the north and is probably ground moraine overlain by thick lake deposits.

The northwest portion of the township, principally Secs. 4 to 9, is typical of the rocky portions of the Superior upland. In Sec. 6 the St. Louis River originally flowed in a shallow channel to a point about a quarter of a mile north of the southeast corner of the section, where it plunged by a series of falls and rapids into a short rock gorge beyond which the valley sides are in the surficial lake deposits and drift. At present the river is diverted by a dam into a canal which crosses the upland north of the river to the power plant in Sec. 11. Thomson reservoir is formed by the dam and covers a considerable area in Secs. 5 and 6, with many rocky islands projecting above reservoir level.

GEOLOGY

Rock outcrops are confined to the area along the St. Louis valley, comprising the two northern tiers of sections. Most of these outcrops are a part of the Thomson formation and consist of slate, graywacke slate, and graywacke. Locally there are dikes and irregular intrusives of diabase and in Secs. 1 and 15 there are exposures of the Keweenawan Puckwunge formation, with possibly the Fond du Lac sandstone in the eastern portion of Sec. 1. Exposures are so numerous in Secs. 4, 5, 6, 7, 8, and 9 that space does not permit a detailed description, but some of the more important or unusual features will be described briefly.

Most of the outcrops occur as ridges (*roches moutonnées*) elongated in an east-west direction because the prevailing strike of both bedding and cleavage is in that direction (Figure 6). For convenience the description will start at the northwest corner of the township and progress downstream.

In many of the outcrops it was noted that the ridge came to an abrupt end; this was noted particularly in the northwest quarter of Sec. 6, but probably applies more or less to all the northwest portion of the township. It was found that joints and apparently faults, in some cases, caused the abrupt end of the ridges. At places dikes of diabase followed the joint or fault, and, since the diabase is less resistant to weathering than either slate or graywacke, the ridge may end or a gap exist in some ridges. Many diabase dikes strike about N. 30° E.

Locally, on the islands in the Thomson reservoir and on the east bank of the mouth of the river where it enters the reservoir, there are local folds. The ridges which form the islands are a series of synclines and anticlines forming small points and bays, particularly at the west end of the islands.

In Sec. 7 the west and south tiers of forties have few outcrops, but the remainder of the section has a very large number, many of them bare of vegetation due to recent fires. The exposures consist of the usual alternation of graywacke and slate beds, and cleavage is highly developed in the slate beds. The slates are generally devoid of bedding, and concretion zones often furnish the principal evidence of bedding in outcrops where graywacke beds are absent. The ridges often end abruptly at joint planes or diabase dikes. Aerial photographs of the region near the river suggest faulting with resultant displacement of ridges along the dike zones. Dikes 20 and 40 feet wide were measured at favorable places.

Sec. 5, which includes the east end of the Thomson reservoir, also has a great many outcrops, including *roches moutonnées,* which project above the reservoir level to form islands. More local folding is found north of the reservoir than in most areas of the Thomson formation. In the NW¼, NW¼ of the section is an excellent pitching syncline with a smaller and more closely folded anticline on the south limb. The syncline is well outlined by massive graywacke beds which curve around with smooth dip slopes symmetrical with respect to an east-pitching axis. Successive beds offlap from west to east. The north limb of a similar fold is exposed in the northeast quarter just east of the Midway River. This fold shows up conspicuously on an aerial photograph, but it was found that the curvature shown on the photograph had been accentuated by the topography.

Along the canal, especially near the gatehouse, is an excellent vein of dolomite with considerable quartz. Other veins are mainly quartz. Scattered chalcopyrite was observed in the rock excavated from the channel.

The area of outcrops of Sec. 5 continues eastward to about the middle of Sec. 4, beyond which bedrock is deeply buried under glacial drift. There are also local folds in this area, particularly in the southwest corner.

Although there are some outcrops on the upland in Secs. 8, 9, and 10, the extensive exposures are in the channel of the St. Louis River, which is essentially dry except in times of high water. Above the mouth of Otter Creek, the St. Louis River has cut a narrow gorge in the slates and graywacke, but below that point the river has entrenched itself only slightly in the bedrock.

South of the river and crossed by both the Great Northern and Northern Pacific tracks in Sec. 8 is a large outcrop over a quarter of a mile in length. East of the tracks this exposure contains a considerable number of quartz veins, some showing complicated ptygmatic folding. Several diabase dikes occur in the series of exposures in the western portion of the section. All strike about N. 30° E. Along the river channel in Secs. 8 and 9 the exposures are practically continuous and so much detail is available that it can only be summarized. The structure of the slate is generally simple. There is a nearly east-west strike. South dips are common. Locally there are small folds which are in some cases clearly outlined by the reefs in the frequent pools of water. Concretions are very abundant in many of the beds and have often been dissolved out by the river waters, leaving pocked surfaces. No doubt the organic acids of the river water which came from swamps farther upstream were fairly effective in dissolving the carbonate. Diabase dikes are numerous, particularly in Sec. 9, and these strike up to 30° north of east. In the NW¼, NW¼, Sec. 10, is a more complex diabase intrusive which is partly sill-like. The slate beds near it are contorted and also baked. At places the diabase cuts across the beds as dikes, evidently projecting from the larger sill-like mass. The diabase formed a series of rapids and falls in the river below which the river split into four channels. Outcrops are extensive only in the largest, which is second from the west bank. Near the south end of this channel is a small but important outcrop. It con-consists of a small remnant of Puckwunge conglomerate lying directly on the Thomson slate. This is the unconformity between the Huronian and Keweenawan formations. Most of the exposure consists of a coarse quartz pebble conglomerate with a sandy and shaly matrix. The highest bed is largely sandstone and contains pyrite concretions precisely like those exposed on Little Creek in Sec. 1. The pebbles are 95 per cent vein quartz, but chert, jasper, and slate pebbles also occur. The largest measured was 3 by 5 inches. The slate strikes N. 70° E. and dip 45° S. The conglomerate varies in attitude but generally seems to strike N. 60° E. and dip 10° S.

The only other exposures downstream on the St. Louis in this township are on Little Creek in Sec. 1, where slate and Puckwunge conglomerate are nearly in contact, and a sandstone and conglomerate of the Middle Keweenawan type are exposed a short distance above. Various outcrops of slate and graywacke occur along the creeks in Secs. 1, 2, and 3.

Township 48 North, Range 17 West

SURFACE FEATURES

This township shows considerable variation in surface features, but in a broad way may be considered fairly typical of the Superior upland (Plate 7). Although rock outcrops occur, the topography is largely controlled by glacial features including drainage of waters ponded in front of the Superior lobe. Large areas are covered by terminal moraine with extensive areas of outwash beween the morainic belts.

Much of the southeast portion of the township, from Sec. 12 diagonally across to Sec. 30, consists of rather pronounced morainic topography with several lakes and ponds of which Chub Lake is the largest. Much of this moraine seems to have a thin veneer of sandy outwash. In Sec. 35 and portions of adjacent sections is a level outwash area extending southward across the town line. Part of this was originally a shallow body of water known as Hay Lake, but it is mostly marsh land at present.

There are smaller belts of terminal moraine in the northwest portion of the township and larger areas of outwash now crossed by Otter Creek and its tributaries in the north and by the Blackhoof River in the southwest corner (Plate 4).

An important feature of the topography is the valley which extends southwestward from Carlton to the northwest corner of Sec. 30. The level valley floor is followed by the Northern Pacific Railway and Highway 61. This valley was formed by the overflow of glacial Lake St. Louis,[1] which flowed down the present valley of the St. Louis River to Scanlon, where it encountered the ice of the Superior lobe and was diverted southwestward to the Kettle River drainage. Winchell originally described this channel and it has been discussed in some detail more recently by Leverett.[2] The numerous outcrops along the valley are a result of the scouring effect of the glacial waters which swept along the valley for some time until drainage of the Superior lobe was diverted elsewhere.

Very extensive gravel deposits in Secs. 2 and 3 and northward into T. 49 N. must have formed by outwash from the Superior lobe before the formation of the drainage channel noted above. Most of the northwest corner of the township consists of a level, sandy outwash plain. Some of the more rolling portions probably represent a veneer of sandy outwash over low terminal moraine deposits.

Extensive areas of swamp and marsh land in Secs. 17, 18, 19, 20, 21, 29, and 30 probably resulted from extensive deposition of outwash along the valley formed by the outlet of glacial drainage, probably during the waning stages. The plain thus formed is too level to permit proper drainage. The region to the east of the swamps in Secs. 15, 22, 27, and adjacent areas has very sandy soil, much of which suggests outwash over rather typical morainic topography. Gravel deposits are also numerous throughout the higher areas of the southern half of the township.

GEOLOGY

As noted above, the outcrops occur almost exclusively along the channel of the glacial drainage which extends from Sec. 1 southwest to

[1] N. H. Winchell, "Glacial Lakes of Minnesota," *Bulletin of the Geological Society of America*, 12: 109–28 (1901).

[2] Frank Leverett, *Moraines and Shore Lines of the Lake Superior Region*, (United States Geological Survey Professional Paper 154-A, 1929) p. 55.

Sec. 30. Several outcrops also occur along the valley of the Blackhoof River in Sec. 31. All the rock exposures in the township belong to the Thomson formation and later diabase dikes. The features of the formation have been described in some detail in Chapter III and only local features will be emphasized here.

The outcrops in Sec. 1 are an extension of the abundant series found in the city of Carlton and vicinity. The beds consist of both slate and graywacke. A 25-foot-wide diabase dike is exposed near the overpass of Highway 61. Local folds are well exposed on the Great Northern Railway a few hundred feet northwest of the overpass. A small quarry in the NE¼, NW¼, reveals some of the features of the slate beds exceptionally well. Coarse clastic grains in graywacke occur in outcrops just north of the south quarter corner of Sec. 2.

In Sec. 12, south of the Northern Pacific station there is a long ridge (*roche moutonnée*) of slate and graywacke. On the north side the slaty cleavage is highly developed, and fracture cleavage has cut this slate into rhombic slabs which are unusually diagrammatic even in this area of good slaty and fracture cleavage.

Outcrops are extensive along Highway 61 in Sec. 16, and many long rock ridges project above the swamp level south of Little Otter Creek. Many features of the formation are well shown in this extensive series of exposures. Concretions of many sizes are abundant and mark the trend of the bedding across outcrops. A long outcrop on the south section line shows extensive faulting of a brittle graywacke bed in slate.

The outcrops along the highway in the NW¼, NE¼, are mentioned by Winchell, who thought some beds were conglomerate. Some of the scattered siliceous pebbles (?) may rather be small chert concretions. In fact, they are so classified in the present investigation. Other outcrops here show cigar-shaped and disc-shaped concretions which consist mainly of carbonate.

A small outcrop occurs along the road north of the southwest corner of Sec. 17. Because of the fresh rock exposed, fragments of the concretions which occur here were collected and analyzed.

Some of the exposures in Sec. 31 along the valley of the Blackhoof River are important because they vary from black slate to phyllite. This is the farthest north that metamorphism of the Thomson formation to the stage of phyllite has been recognized. As the exposures are traced southwestward the metamorphism becomes progressively more severe. The phyllitic beds in Sec. 31 are minutely folded and vein quartz is present at places (Figure 9).

Township 49 North, Range 15 West

SURFACE FEATURES

This township includes the full range of topography from the low flood plain of the St. Louis River to the glaciated Superior upland in the northwest corner of the township (Plate 8). The portion of this township along the river is a part of the city of Duluth and details of rock exposures are described in Chapter VII.

The relatively level area along the St. Louis River, as well as a large area on the Wisconsin side, is a thick alluvial deposit that represents a filling of the extreme southwestern end of the Superior basin. Its present character is that of a flood plain perhaps 50 feet above the present water level in the river, which is fairly well ponded by Minnesota Point. Much of the material in the flood plain was deposited in glacial Lake Duluth.

A high bluff of Duluth gabbro extends across the township from Sec. 12 through Secs. 13, 14, 22, 23, 27, and 34. This bluff turns westward in Sec. 34 and forms a rounded bluff facing south, then turns abruptly northward at the western line of Sec. 33. Northward the bluff is less pronounced but extends through Secs. 29, 20, and 17, where it fades out. In general this bluff marks the west margin of the gabbro and lava flows as shown on Plate 8.

The southwest corner of the township is deeply eroded by Mission Creek and its tributaries. Examination of the steep sides of the valley shows that the creek is entrenched in a thick deposit of glacial lake clay, and landslides often develop in the plastic clay when the slopes are over-steepened by stream erosion. It is evident from these deposits that glacial Lake Duluth extended up the valley of Mission Creek as far as Highway 61. Portions of Secs. 29, 30, 32, 33, and 34 and all Sec. 31 are covered by red lake clay deposited in glacial Lake Duluth.

The upland of the northwest portion of the township is rolling, containing areas of swamp between higher areas where the glacial drift forms a thin deposit on the rock surface. Most of the area has a weak terminal moraine topography except for a belt of ground moraine in Secs. 4 to 9. Small outcrops of slate, basalt lava flows, and gabbro occur at intervals in their respective areas as shown on Plate 8.

GEOLOGY

The western tier of sections in this township is underlain by Thomson slate. Exposures occur along the valley of Mission Creek in Secs. 30 and 31, in the western portions of Secs. 17 and 20, and along the headwaters of the Midway River in Sec. 1. The exposures consist mainly of slate with interbedded graywacke. Much of the slate has been somewhat metamorphosed along the east side of Sec. 6 as a result of having been overlain by lava flows and the Duluth gabbro before erosion limited its westward extent. In some exposures cleavage of the slate has been largely destroyed by recrystallization, and the rock may properly be called a hornfels, a fine-grained rock resulting from recrystallization by heat. In the NW¼, SE¼, Sec. 6, a porphyritic diabase dike about 175 feet wide cuts the slate and graywacke beds.

Several exposures of the slate occur in Secs. 17, 18, and 20. The most important are the exposures along the line between Secs. 17 and 20, where the slate occurs within 350 feet of the Keweenawan basal conglomerate and sandstone that lies nearly horizontally on slate with bedding at 85° to the horizontal. The sandstone is in turn overlain by the lowest known Keweenawan lava flow of the Duluth region. To the south the contacts between the slate, sandstone, and flows are buried beneath glacial drift and glacial lake deposits. The exposures in Secs. 32, 33, and 34 are among the most extensive and interesting of the area. All outcrops west of the center of Sec. 33 consist of lava flows with rare dikes of diabase. Near the contact with the gabbro, a short distance east of the center of Sec. 33, the lava flows have been considerably recrystallized by the heat of the gabbro intrusive, forming basalt hornfels. Practically the exact contact of the base of the gabbro with the underlying metamorphosed flow may be seen just north of the Duluth, Winnipeg and Pacific Railway tracks on the west side of the east branch of the small creek in Sec. 33. The contact effect on the lava flows gradually fades out to the west, and the effect is slight at and west of the railroad tunnel. On the hill above the tunnel (Figure 14) there is a series of huge steps or rock terraces, each representing a different lava flow. A minimum of ten lava flows is indicated on this hillside.

The gabbro forms the large hill in Secs. 33 and 34 that culminates in Bardon's Peak. Along Skyline Parkway around Bardon's Peak the gabbro is well exposed in road cuts and is conspicuously banded (Figure 17) with alternating zones of troctolite (gabbro composed of feldspar and olivine) and feldspathic gabbro. The gabbro exhibits various facies along the bluffs facing the St. Louis River.

A few outcrops of special interest deserve brief description. At the northeast corner of Sec. 6 and extending into adjacent sections around the road intersection is a series of outcrops of metamorphosed basalt flows (hornfels) that are cut at places by a pegmatite consisting mainly of plagioclase feldspar and hornblende. On the north side of the road the hornfels retains the original amygdaloidal texture.

Near the north quarter corner of Sec. 17, small outcrops of gabbro occur south of the road. Here the gabbro contains very coarse pyroxene and also basic pegmatitic patches.

An excellent outcrop of Lower Keweenawan sandstone occurs on a west-facing bluff a quarter of a mile north of the south line of Sec. 17 and about three-eighths of a mile from the road on the west line of the section. Here the main portion of the sandstone is buff, cross bedded, and slightly silicified. Close to the contact the sandstone is conspicuously banded, light and dark, and is highly silicified and baked in appearance.

One quarter of a mile east of the west quarter corner of Sec. 28 is a large series of outcrops of basalt hornfels with excellent quartz orthoclase pegmatite dikes up to 6 inches in width.

The northeast quarter of Sec. 29 also has extensive outcrops of basalt hornfels. Exactly 325 paces south of the northeast corner of Sec. 29 is an exceptionally fine example of a hornfels derived from an amygdaloidal basalt. The amygdules are arranged in layers and have been metamorphosed to anhydrous silicates and quartz.

Township 49 North, Range 16 West

SURFACE FEATURES

The surface features of this township are, to a considerable extent, controlled by the St. Louis River and its tributaries. The river enters from the west in Sec. 18, flows southward, and leaves the township in Sec. 31 (Plate 9). Because of the large flow of glacial water when the river drained glacial Lake St. Louis farther to the north, the drift was largely swept away from Secs. 19, 30, and 31 and portions of adjacent sections. Large boulders concentrated from the drift are characteristic of portions of this flood plain. Rock exposures are also very abundant over this area. The remainder of the township consists of extensive areas of poorly developed terminal moraine varying to disconnected areas of ground moraine. Considerable portions could be classified as either terminal or ground moraine. In the southwest part of the township, Secs. 19, 29, 30, 31, and 32 and portions of 18, 20, and 33 comprise a large outwash plain with a prevailing sandy soil (Plate 4).

Superimposed on this glacial topography is a fairly well-developed stream pattern of tributaries of the St. Louis River, Midway River being the most important. A dendritic stream pattern is rarely well developed in areas of young glacial drift such as that of the Superior lobe. It is probable that the development here is largely a result of the relatively steep gradient of the small streams as they approach the gorge of the St. Louis. In spite of the valleys thus developed, erosion has exposed bedrock only near the main streams; the northern portion of the township has no outcrops. Swampy areas are common along the headwaters of the streams.

The soil varies from red clay or reddish gravelly clay to gravel, and boulders are abundant in many areas, particularly some of the gently rolling areas of ground moraine. Other areas seem surprisingly free from boulders. Gravel pits are common in the moraine areas, and stratified sand and gravel are well exposed at places. The presence of these pits in some of the areas which Leverett classified as till plain suggests that they may be more properly classified as a weak terminal moraine.

The Midway River and some of the other tributaries of the St. Louis River have well-developed terraces a few feet above the present stream levels. This suggests that perhaps their valleys were eroded during the late glacial stage, when drainage was much heavier than at present and the stream gradients were controlled by the level of glacial Lake Duluth.

The southeastern corner of the township was covered by the waters of Lake Duluth. The general beach level corresponds with the Northern

Pacific Railway, but once extended considerably farther up the creek valleys. At most places the beach is indistinct, but the characteristic red lake clays cover much of the area of Sec. 36 and extend into adjacent areas.

GEOLOGY

The outcrops, as previously noted, are very abundant in the southwest portion of the township along the glacial flood plain of the St. Louis River.

The St. Louis River enters the township in the SW¼ of Sec. 18, and rock outcrops are continuous along its east bank. A fault zone is exposed on the north bank at the point where the river course changes from east to south, and a large breccia islet occurs in the stream opposite the plant of the Northwest Paper Company. The breccia consists of slate fragments with more or less vein quartz. The strike of the breccia from islet to islet in the stream is N. 8° W. On the east bank opposite the paper plant an anticline and syncline may be easily recognized. The prevailing rock here is graywacke. In Sec. 19 and extending eastward in Sec. 20 is an area of a great number of outcrops. A dam near the south side of the section maintains a pool at an approximate elevation of 1121 feet.

On the Great Northern tracks just north of the Cloquet south city limits is an exposure of slate with peculiar carbonate lenses which has been described in some detail in the description of the Thomson formation in Chapter III. The general strike of the beds throughout this section is east-west, but the dips vary from north to south, depending on the position on local anticlines and synclines, which can best be recognized along the low rocky gorge of the river. Over much of Secs. 19 and 20 slate outcrops predominate almost to the exclusion of graywacke. This is also true of the adjacent area to the south. A road cut just west of the underpass of Highway 45 at Scanlon exposes slate with well-developed slaty cleavage parallel to the bedding. Fracture cleavage cuts the flow cleavage blocks into rhombic and other shaped slabs. Outcrops are not particularly abundant in Sec. 30. Much of it is swampy, but south of Highway 61 there are numerous slate exposures, and near the south line graywacke forms many outcrops.

In Sec. 31, and to a lesser extent in Sec. 32, outcrops are again abundant, except in some swampy areas. A dike may be traced across the southwestern portion of the section to the river. Along the east bank of the river, exposures are continuous for considerable distances and anticlines and synclines may be recognized at several places. Rapids and low falls are formed in the river by the reefs of dipping beds, particularly graywacke.

A few outcrops of slate and graywacke along the creeks in Secs. 35 and 36 are important, principally because they show the extension of the Thomson formation eastward to the ridge formed by the Keweenawan rocks, including conglomerate, sandstone, basalt flows, and gabbro.

Township 49 North, Range 17 West

SURFACE FEATURES

This township, over much of its extent, is a level to gently rolling sandy outwash plain. The St. Louis River has cut a trench through the upland and then formed a well-defined terrace within which it has cut its present relatively narrow channel (Plate 10). The larger trench was cut late in glacial time when glacial Lake St. Louis drained down the valley. The uniformity of the surface is also interrupted by local, relatively small belts of terminal moraine in the eastern and southern portion of the township. West of the St. Louis River is a north-south belt of ground moraine (Plate 4); there is also a small area in Secs. 17 and 18. Because of its relatively level topography, the streams, except the St. Louis River, are sluggish, and rather extensive areas of swamp indicate the comparatively poor drainage of the area.

Some of the terminal and ground moraine areas are characterized by numerous boulders, as seen, for example, in Sec. 1. In the southeast corner of Sec. 2 is a fairly high knob with a gravel pit on the south side, exposing stratified fine gravel and sand with a few boulders. This is evidently a kame. In general, the area north and east of the river consists of rather pronounced terminal moraine, varying to more nearly level areas of ground moraine.

Much of the western portion of the township consists of a level to gently rolling outwash plain, especially in the area of the Cloquet Forest of the University of Minnesota,[3] which lies in Secs. 29, 30, 31, and 32. This and adjacent areas have mainly sandy soils, varying from loamy sand to sandy loam, except for the swampy areas, which are underlain by peat. Much of this area may be a mantle of sandy outwash over a gentle morainic area. At the quarter corner between Secs. 16 and 17 is a curved ridge of sand which may be a short esker, or an elongated kame. The limited areas of ground moraine such as that in Secs. 17 and 18 have a gravelly clay soil with boulders and thus is in decided contrast with the sandy soils of the adjacent outwash areas.

Cloquet is located on the higher part of the terrace along the St. Louis and on a rolling to hilly remnant of terminal moraine bordered on the south by both the valley of Otter Creek and a low swampy extension of the valley which forms a low area connecting with the St. Louis River terrace to the east. The drainage now carried south by Otter Creek once seemed to have flowed directly east to the St. Louis. At the southwest corner of Cloquet there is a fairly pronounced valley leading south toward Otter Creek, but there is no creek in this valley at present.

In Secs. 25, 35, and 36 is the north end of a very large blanket-like deposit of gravel which forms a high area between the valley of Otter Creek and the St. Louis River. This mass of gravel was probably laid

[3] For an extensive description of this forest, see "The Cloquet Forest" (University of Minnesota Agricultural Experiment Station Technical Bulletin 112).

down by outwash from the ice front when it stood along the present course of the St. Louis and over the site now occupied by Carlton. This gravel deposit has been used on a large scale both on the east and west sides.

GEOLOGY

The only rock exposures are along the valley of the St. Louis River in Secs. 13, 14, 24, and 36, where the flood waters of glacial drainage swept the surficial material away down to the bedrock. In Sec. 13 the St. Louis River now flows fairly close to the north bluff of its trench, so that outcrops are not numerous on the north side of the stream, but south of the river there is a relatively level terrace as much as half a mile wide where rock exposures are exceedingly numerous. Most of the city of Cloquet lies on the higher land just south of this rocky terrace.

Both north and south of the river in Sec. 13 graywacke and slate beds alternate. Graywacke beds predominate at places. As much as 25 feet of massive graywacke without a slaty parting was noted. At about the north boundary of the south tier of forties, however, is a pronounced change with mainly slate exposed to the south. In the channels below the dam the beds are well exposed and the details can be easily observed. Concretions are very abundant in certain zones. In some beds the concretions coalesce, forming irregular knobby masses. Beds were observed which seem to be as much as 25 per cent concretions. Massive graywacke beds often seem a favored place for concretions. Where slate beds occur between graywacke beds, the cleavage in the slate forms a more acute angle to the bedding than in the graywacke. Locally, the graywacke is coarse-grained, as in an outcrop projecting into the river near the center of Sec. 13. In Secs. 13 and 14 carbonate lenses occur in many of the slate beds. These lenses clearly cross the bedding at a wide angle; often the slate lenses beween the carbonate lenses are very thin.

South of the river in Sec. 13 many of the rock exposures are small and do not form the long ridges characteristic of so much of the Thomson formation. It was observed that the strike of the cleavage is parallel to the strike of the bedding where the long ridges occur and that there is a wide angle between the two where the ridges are poorly developed.

Extensive outcrops of slate occur along the east side of Sec. 36. There is a notable absence of graywacke in this section. To the north, in Sec. 25, there is a good exposure of graywacke crossed by the Northern Pacific tracks.

Township 50 North, Range 15 West

SURFACE FEATURES

This township is located far enough from the shore of Lake Superior to be characteristic of the Superior upland. It is underlain entirely by Duluth gabbro, and scattered outcrops indicate that the glacial drift is rather thin (Plate 12). The rolling topography with considerable areas of swamp, especially along the streams, is probably indicative of a rather gentle relief of the gabbro surface modified by deposits of ground moraine that have in turn been only slightly entrenched by the small streams.

The township except for the southeast part is drained by the headwaters of the Midway River. A fairly well-defined drainage pattern has been developed, a fact not characteristic of most streams in a glacial topography. Examination of the rather broad swamp valleys of even small tributaries leads to the conclusion that in immediately postglacial time, or probably during the waning stage of glaciation, a great deal of water flowed along these valleys. The current was doubtless swift owing to the rapid fall of the streams on their way to Lake Superior.

The area between the streams is gently rolling and cleared fields normally reveal an abundance of glacial boulders. A considerable portion of the area is covered with poplar and other small trees and shrubs.

A few small areas have a low hummocky topography and, at places, these are along ridges somewhat above the general level. On first thought one might well consider such ridges as isolated areas of terminal moraine. Further investigation, however, usually reveals outcrops of gabbro not far away, and it is fairly certain that such hilly zones are merely ground moraine over a rocky ridge. Small areas of terminal moraine were mapped in Secs. 7, 18, 23, 24, 26, and 27, and in Secs. 25, 35, and 36. Glacial striae on a low outcrop near the southwest corner of Sec. 34 indicate that the ice moved in a direction S. 55° W.

GEOLOGY

This township, on the basis of its location and scattered outcrops, is believed to be entirely underlain by the Duluth gabbro. The glacial drift is generally thin and this combined with the solid ledge of gabbro beneath is a fact of considerable importance. It means that water for the numerous homes that are being continually built must be obtained from relatively shallow wells in the glacial drift. Once the gabbro is encountered in a well the chance of getting water is very slim. It is fortunate that the glacial drift is generally gravelly and sandy and thus produces considerable water wherever it is of sufficient thickness. In general, areas very close to outcrops should be examined rather carefully before building and becoming dependent on a very shallow source of water. It is almost inevitable that the water table will drop as the area becomes more settled and the amount of cleared land increased. In that case some homes may be without a convenient source of water.

The gabbro exposed in this township varies from medium- to coarse-grained and is generally feldspathic; that is, it contains considerably more plagioclase feldspar than a typical gabbro as given in standard rock classifications such as that for the northeast part of Sec. 26. At places a banding may be noted—as along the road between Secs. 14

and 23 and at the west side of Sec. 26. The dip of the bands is from 35° to 40° E., varying to southeast and northeast. Some of this gabbro also shows a coarse mottling.

Locally there are coarse segregations of feldspar, pyroxene, and a little magnetite-ilmenite in the area, as is shown by outcrops along the roads and in the fields in the NW¼, NE¼, Sec. 23.

The magnetite outcrops originally discovered by N. H. Winchell are along Hermantown Road just west of the east section line (Haines Road). Several old pits may be seen just west of the church, but magnetite is sparse. South of the road across from the church is an outcrop behind a house. This shows some small red rock dikes.

Near the middle of north side of the section a road cut shows medium-grained feldspathic gabbro varying to a finer grained gabbro with pegmatitic (anorthositic) patches and calcite veinlets.

South of Mogie Lake in Sec. 35 large outcrops show a considerable amount of basalt hornfels, that is, basalt lava flow inclusions in the gabbro. Large outcrops south of the west end of Mogie Lake show very coarse pyroxene segregations in a very coarse, mottled gabbro. Some of the rock has fair banding with troctolite and coarse pyroxene in alternate bands.

At the southwest corner of Sec. 32 there is an outcrop of basalt hornfels and pegmatitic patches.

Township 51 North, Range 12 West

SURFACE FEATURES

This township consists of a triangular fraction lying along the coast of Lake Superior from the mouth of Talmadge River to Stony Point (Plate 13). The trend of the coast line is east-northeast and is fairly regular except for the projection of Stony Point which is caused by a diabase intrusive, as are so many of the projections and bolder parts of the Minnesota coast.

This section of the coast is relatively low and the slope inland is gradual in contrast with the steep bluffs at Duluth. Elevations rise gradually from the 602 feet of Lake Superior to somewhat above 1000 feet in the northwest corner of the township, approximately 3 miles from the lake. Low rock exposures are abundant alongshore although two stretches of about a mile each, in Secs. 9, 2 and 3, have red lake clay banks but no rock outcrops. Inland the rock exposures are principally along the four main stream valleys, Talmadge River, French River, Smith Creek, and Sucker River. In Secs. 4 and 5 a massive ophite forms a low ridge or bluff, trending north-northeast, corresponding to the strike of the flows.

The northeast corner of the township, consisting of Secs. 5 and 6 and the north half of 7 and 8, forms a very level red lake clay plain which slopes gently southeastward. This is part of one of the largest relatively level areas along the entire Minnesota coast. Red clay deposited in glacial Lake Duluth is the prevailing soil over the township except where the rock is exposed.

The streams entering Lake Superior generally have cut a rock gorge for about the last mile of their course. This gorge is commonly 50 to possibly 100 feet deep, as a maximum. A mile or so upstream the erosion has cut through the surficial deposits exposing but not cutting into the underlying rocks. Still further upstream the bed becomes paved with boulders, and outcrops are uncommon.

GEOLOGY

Most of this township is underlain with basic flows, mainly ophites, but with a few thin melaphyres. The flows strike from about N. 25° E. to N. 40° E., which is at an acute angle to the shore; thus successive flows trend inland. The dip approximates 15° SE. Relatively fresh exposures are abundant alongshore and along the stream gorges, but no unusual features were observed. Long ago a diamond drill hole was put down at the mouth of the French River, but evidently nothing of note was discovered. The hole at present has a considerable artesian flow.

The Stony Point diabase intrusive has already been described on page 63. The few included boulders of anorthosite at the base of the intrusive in Sec. 1 are worthy of special note because they are the only anorthosites exposed between Duluth and Two Harbors. Farther up the coast these inclusions are extremely abundant.[4]

Township 51 North, Range 13 West

SURFACE FEATURES

The city limits of Duluth extend across the southern portion of this township, but this area is beyond the built-up portion. Lake Superior cuts across the southeast corner of the township where a low, rocky shore furnishes almost continuous exposures of basalt flows (Plate 14). The surface slopes gently southeastward from the northwest corner toward the lake, but the diabase of the Northland and Lester River sills form ridges approximately at right angles to the slope, that is, in the direction of the general strike of the flows and sills. At places the ridge of the Lester River sill rises 200 feet above the lake plain to the southeast.

The northwestern portion of the township, consisting of all, or portions of Secs. 3, 4, 5, 6, 7, 8, 17, 18, and 19, forms part of a rolling to hilly belt known as the Highland moraine. The south edge of the terminal moraine is at an elevation of approximately 1200 feet and rises northward to maximum elevations at hill tops of about 1375 feet. In Sec. 4 the terminal moraine merges into ground moraine at about 1300 feet. This belt extends from Sec. 3 southwest to Sec. 30. East of this belt the area is a lake plain with the rock ridges previously noted. In Sec. 11 the ridge

[4] F. F. Grout and G. M. Schwartz, *The Geology of the Anorthosites of the Minnesota Coast of Lake Superior* (Minnesota Geological Survey Bulletin 28, 1935).

extended above the highest level of glacial Lake Duluth (Figure 20). The lake plain and, to a lesser extent, the moraine areas are cut by the valleys of the Lester, Talmadge, and French rivers and their headwater tributaries. The prevailing soil of the lake plain is a heavy red clay which is not a good agricultural soil.

The rock ridges formed islands, particularly during the lower stages of Lake Duluth. Well-defined beaches and even sea cliffs occur along the sides of the ridges. As is the case with most streams entering Lake Superior in the Duluth area, the lower portions within a mile or two of the lake cut down to the underlying rock. Farther upstream the rivers flow over a boulder bed in the lake plain or moraine, and outcrops are rare or entirely lacking.

Where streams are entrenched in the lava flows, they are frequently very crooked, as, for example, the Talmadge River in Sec. 24. This is due to the fact that the stream alternates between following the soft zones, usually amygdaloidal portions of flow, and then cutting more or less directly across the strike to the next flow.

GEOLOGY

Along the coast of Lake Superior exposures of basalt flows are almost continuous. These consist of a large number of relatively thin flows, most of them melaphyres, that is, dense textured basalts; but a few ophites and porphyrites are interbedded with the melaphyres. A felsite also occurs in Sec. 34, nearly a mile southwest of the Lakewood Pumping Station. A number of the flows exposed alongshore also crop out in the gorge of the Talmadge River. The rhyolites are the best horizon markers, and correlating those exposed on shore with those on the Talmadge River indicates a strike varying from N. 25° E. to N. 30° E.

The conspicuous geologic feature of the township is the ridge of Lester River diabase which shows extensive outcrops from Sec. 33 northeastward to Sec. 1. The general character of the sill has been described on pages 61 to 62 and only a few additional details need be mentioned.

In Sec. 7 on the East Lester River and on a hill to the south are limited exposures of intrusives which must be just about at the top of the Duluth gabbro. From their character, however, the rocks are believed to be related to the Endion diabase sill. The exposure south of the river is a medium-grained diabase with gray feldspar. On the north bank of the river is a mixture of coarse, mottled diabase, pegmatitic diabase, and reddish, medium-grained diabase or granophyr. There are also small red aplite stringers.

Where the Talmadge River crosses the Lester River, and extending somewhat downstream in Sec. 14, is an extensive series of exposures of an intrusive complex. The farthest upstream outcrop is in the NW¼, SW¼, Sec. 14, and consists of ordinary diabase of the type exposed on the ridges both north and south of the valley. Downstream are exposures of intermediate rock, that is, a mixture of diabase and granophyr. Below this is a considerable stretch of diabase with some red feldspar, but near the north-south center line the rock again grades through intermediate rock to typical granophyr. Downstream both rhyolite and basalt are exposed.

An intermediate rock is also exposed on the road about a quarter of a mile west of the southeast corner of Sec. 19. This is a dark rock with streaks and patches of red rock which seems related to joints.

Both intermediate rock and granophyr also occur in the NE¼ of Sec. 30.

Township 51 North, Range 14 West

SURFACE FEATURES

Since this township lies far enough back from Lake Superior, it is relatively little affected by the steep slopes along the lake. Most of the topography of the western half is rolling ground moraine with low swampy areas and a very poorly developed drainage system. Boulders are abundant in this area. Wild Rice Lake along the western border is a large shallow lake with a few rocky points and inlands (Plate 15). The elevation of the lake is controlled by a dam at the outlet in Sec. 7. During high water, water is stored to be released during low water to add to the flow in the Cloquet River which in turn flows into the St. Louis River, where power is developed along its lower course.

The eastern portion of the township from Sec. 1 through Secs. 12, 13, 14, 22, 23, 24, 27, and 28 has a mild hilly to hummocky topography (Plate 4). This is a branch of the Highland moraine. Southeast of this moraine belt there is an outwash plain in Secs. 25 and 26 and small portions of adjacent sections. This outwash lies on the side of the moraine from whence the ice came and it is probable that it developed as the ice retreated and a ponding took place behind the Highland moraine.

In Secs. 34 and 35 it is evident that at one stage the outwash area drained southward through Sec. 34 to Tischer's (Congdon) Creek. This was presumably when Amity Creek valley was still blocked by ice. As the ice retreated the present drainage, via the west branch of Amity Creek, was established and an abandoned creek valley was left diagonally across Sec. 34 from northeast to southwest (Plate 15).

GEOLOGY

Terminal and ground moraine deposits are fairly heavy in this township; outcrops are thus rather scarce except in the southeast portion where a position nearer to Lake Superior has resulted in steeper slopes and probably less deposition by the ice of the Superior lobe. The entire township is underlain by the Duluth gabbro and its associated rock facies.

Exposures of rock are fairly extensive in Secs. 25, 35, and 36. In Sec. 25 a large area of outcrop exists north of the University of Minnesota

Experimental Farm. This consists of coarse, mottled gabbro with pegmatitic patches, magnetite segregations, and coarse pyroxene crystals. In the southeast corner of Sec. 36 is an extensive series of exposures of red granite. This is medium-grained and consists mainly of red feldspar and hornblende. Thin sections of such rocks normally show much fine-grained quartz.

Along a diagonal road in the northwest portion of the section occurs reddish, medium-grained diabase grading to red granite.

A long gabbro ridge extends diagonally across the NW¼, Sec. 35. This is anorthositic gabbro varying to a normal gabbro. Magnetite is abundant in the anorthositic portion. Gabbro with more or less red granite crops out abundantly along the valley of Amity Creek. A 4-inch dike of magnetite was noted northeast of the creek at about the middle of the NE¼, SE¼, Sec. 35.

Large exposures of coarse-grained gabbro with coarse, mottled pyroxene patches occur north of the dam at the outlet of Wild Rice Lake. Several low outcrops of gabbro occur in Secs. 18 and 19 on the shores and islands of Wild Rice Lake. These vary from dark, coarse-grained gabbro to a lighter colored feldspathic gabbro. One inclusion of anorthosite about 9 by 24 inches was noted in fine-grained gabbro on a wooded island west of the center of Sec. 19.

Several gabbro outcrops occur along the road between Secs. 29 and 30. This consists of coarse, diabasic feldspathic gabbro with some diabase pegmatite patches and stringers. Toward the north a coarse gabbro contains inclusions of a very coarse gabbro.

Township 51 North, Range 15 West

SURFACE FEATURES

This township is located on the upland away from Lake Superior and owes its features almost entirely to deposition of glacial drift unmodified by stream erosion. The greater portion of the township consists of ground moraine and has a high percentage of swamp (Plate 16). Wild Rice Lake occupies a large area in Secs. 13 and 24, and a large adjacent area is subject to overflow when water is stored to equalize the flow in the St. Louis River during dry weather. Similarly a large area in Secs. 5, 6, and 8 are subject to overflow, and considerable areas are practically inaccessible much of the time. Another large area of swamp land in Secs. 2, 3, 9, 10, and 11 and small parts of Secs. 4, 15, and 16 were ditched many years ago in an attempt to make good agricultural land. This seems to have failed as it has in many areas where the peaty soil was not found suitable for most purposes. The land between the swamps is rolling and at places has many boulders. It is good agricultural land when cleared and the boulders removed. The glacial drift is probably not very thick throughout most of the area as indicated by scattered outcrops of gabbro.

A portion of the western part of the township has a somewhat rougher topography characteristic of terminal moraine. This extends in a narrow belt through Secs. 4 and 9, widening out in Secs. 17, 19, 20, 28, 29, and 30 (Plate 4). A large portion of Sec. 29 is level, probably an outwash plain that extends southwest into portions of Secs. 31 and 32.

GEOLOGY

As previously noted this township is largely underlain by gabbro that occurs as scattered outcrops. From magnetic data it has been determined that the base of the Duluth gabbro intrusive is located in the western portion of the township, trending nearly due north from the southeast corner of Sec. 31 to near the northwest corner of Sec. 20, thence somewhat east of north to the northeast corner of Sec. 5. The area to the west is probably underlain by slate such as that found at Carlton.

Outcrops of gabbro are known to be present in the southeast quarter of Sec. 8 and in the western portion of Sec. 9. These were not visited during the present investigation owing to high water in the swamps. Outcrops in the northern portion of Sec. 16 and extensions of these outcrops in Sec. 9 were visited. These consist of coarse gabbro varying to a feldspathic type. Similar feldspathic gabbro is exposed along the highway on the south line of Sec. 17, near the southeast corner of Sec. 16, the southwest corner of Sec. 15, and the northeast corner of Sec. 15.

Several exposures occur along both sides of the road between Secs. 29 and 32. These also are feldspathic gabbro. Finally a medium coarse-grained gabbro is exposed south of the road about a quarter of a mile west of the northeast corner of Sec. 36. Glacial striae on this rock show the ice moved in a direction N. 65° W.

Township 52 North, Range 11 West

SURFACE FEATURES

This township, as is the case with many others along the north shore, has a triangular shape because of the northeast trend of the coast of Lake Superior (Plate 17). Rock outcrops are nearly continuous alongshore except near Two Harbors, where red lake clay overlies the rocks in the bays. The shoreline is notably regular from the Knife River to the headland south of Agate Bay. Along this stretch of coast the flows strike practically parallel to the shore, or perhaps it would be better to say that the coast trends parallel to the strike of the flows, since the structure of the flows is no doubt responsible for the nature of the shoreline.

The Knife River and its tributaries have eroded a wide valley in the northwestern part of the township. This valley also follows the strike of the flows and was occupied by an arm of glacial Lake Duluth. It is well filled with red lake clay forming a nearly level plain in Secs. 4, 5, 6, 7, 8, and 18. The general elevation of this plain varies from 950 feet near the Knife River to 1000 feet at its sides. The Knife River has an elevation of approximately 935 feet at the southwest corner of Sec. 4 and drops to

835 feet where it leaves the township near the southwest corner of Sec. 19. In general it is entrenched about 50 feet in the lake plain.

Between the Knife River and the shore of Lake Superior is a long rocky ridge of basalt flows which ends in Sec. 9, except for a few outlying rock exposures in Secs. 3 and 4. This ridge was evidently an island in the lower stages of the glacial lakes because lake clays extend from the Knife River valley in Sec. 4 eastward to Two Harbors. The upper beach level of Lake Duluth north of Two Harbors is given at an elevation of 1115 feet by Leverett.[5] At that stage all of this township was covered by water, but glacial sediments probably were not deposited on the rock ridges to any extent; they were swept into the lower areas such as the Knife River valley. (The prevailing soil of the lower areas is red lake clay.) As the glacial lake levels lowered, certain levels were maintained long enough at places to form well-defined sea cliffs and beaches.

GEOLOGY

The greater portion of this township is underlain by lava flows. Alongshore in Sec. 31 and on Knife Island are exposures of diabase which appear to be a dike offshoot of the Stony Point intrusive. The flows exposed alongshore are listed in Chapter III; little additional description is needed. The flows at and near Two Harbors are melaphyres which are particularly well exposed between Agate and Burlington bays. All the flows, twenty-three in number, exposed between the Knife River and Sec. 11 just west of Agate Bay, are ophites of varying thicknesses.

The ridge which extends from Sec. 30 northeast to Sec. 3 has an unusual feature which merits special description. The exposures along the northwest side of this ridge consist of a series of more or less normal basalts, but along the crest and southeast slope the rock is fresh appearing and has a fine hornfels or granoblastic texture.

Exposures of this hornfels type of rock were noted at the village of Knife River and to the west, where they were believed to be ordinary hornfels resulting from the intrusion of the Stony Point diabase. Northeast of Knife River, however, there are no diabase intrusives, but the hornfels continue the full diagonal length of the township. The rock is definitely an extrusive as amygdaloidal zones were observed, particularly in a pit just north of a house in the NW¼, NW¼, Sec. 16. No explanation of the cause of the recrystallization is known.

TOWNSHIP 52 NORTH, RANGE 12 WEST

SURFACE FEATURES

Lake Superior barely cuts the southeast corner of this township (Plate 18). It may, therefore, over much of its area, be considered as representative of the less rugged upland area north of Lake Superior. With the

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

exception of a few rock knobs and ridges the area slopes gently to the southeast toward the lake. Elevations in the northwest portion vary from 1200 feet to approximately 1300 feet on the crests. This township furnishes an excellent illustration of the fact that there is not, as has been often claimed, an escarpment along the north shore of Lake Superior. Many small streams have their headwater in the northwestern portion of the township and these form tributaries to the Sucker, West Knife, and Knife rivers.

All of this township which lies below elevation 1100, that is the entire southeast half, was covered by the waters of Lake Duluth. The prevailing soil is a red lake clay (Figure 20). Most of the northwest half of the township consists of rolling ground moraine with small areas of stony terminal moraine in Secs. 3, 4, 6, and 7.

The moraine soils are much superior to the poorly drained lake clay soils. Where nearby fields represent both types, the thrifty grain and potatoes on the moraine soils are noteworthy.

In general, the upper beach of Lake Duluth is not well marked but locally, where slopes are steep, well-defined beaches may be recognized. Such beaches occur on the southeast side of the Red Rock hill in Sec. 2 and around the diabase ridge in Secs. 19, 20, and 30. At places gravel banks mark the locations where temporary streams emptied into the lake or previously deposited gravels were rewashed (Figure 21). Some of these gravels are poorly rounded as if washed for only a short time.

Some of the rock hills, the diabase ridges in Sec. 20 for example, projected above the highest level of Lake Duluth as islands.

The general strike of the flows is shown by exposures from Sucker River in Sec. 33, N. 45° E. to Sec. 26.

Extensive exposures of flows are found along the lower portions of both branches of the Knife River. In Sec. 36 the Knife River is deflected by the diabase of the Stony Point sill so that it flows at an acute angle to its course in the northern portion of Sec. 36.

GEOLOGY

The greater portion of the rock underlying this area is buried beneath the glacial lake clays and ground moraine of the Superior lake. Isolated ridges, mainly diabase, project through the glacial deposits. The streams at places have eroded down to bed rock and locally have cut small gorges in the rocks.

In the northwest corner in Secs. 5, 7, and 8 are three knobs of diabase, more or less in line and doubtless part of a diabase sill or possibly a dike. In Sec. 5 the exposures reveal a coarse- to medium-grained, mottled, olivine diabase. In Sec. 7 medium- to coarse-grained black diabase occurs on two hills.

Cutting diagonally across the township from Sec. 30 to Sec. 2 is a series of disconnected ridges which represent the northeastward extension of the Lester River sill. It is evident that the sill is irregular in character at this northern end and at places consists only of red rock, as on the Sucker River, possibly on the West Knife. Beyond this only red rock is exposed, but diabase facies may exist beneath the drift. Possibly the acidic facies were more mobile than the basic and greater amounts were forced out into the probably thinner sill which exists in this northward extension. The ridge of basalt in Sec. 11 is fresh appearing, somewhat like a hornfels. A small exposure of rhyolite along the line between Secs. 10 and 11 is the only acidic flow exposed in the township. In 1928 and 1929 considerable diamond drilling and exploration by a shaft was carried on in Secs. 25, 26, and 31. The results are referred to in some detail in Chapter IX.

Township 52 North, Range 13 West

SURFACE FEATURES

This township is characteristic of the upland north of Lake Superior. The area consists entirely of glacial topography, mainly terminal and ground moraine of the Superior lobe. There are extensive areas of swamp, particularly in the ground moraine belts (Plate 19). Because of the thick drift mantle, outcrops are rare and occur mainly along the streams. For the most part the outcrops are low and have little effect on the topography. The highest beach of Lake Duluth may be traced across Sec. 36 and it probably extends across the southeastern portion of Sec. 35, but it was not traced in this section. Most of the south portion of the township is underlain by terminal moraine connected to a large area in the north-central portion by a narrow zone in Secs. 21, 22, 27, and 28. Considerable areas of ground moraine occur in the northeast and northwest corners and in areas in the east and west-central portions. At places boulders are very abundant in the ground moraine.

All the central portion of the township is occupied by a wide belt of terminal moraine with the north-central and northwest sections best classified as ground moraine, although the distinction is not always sharp. Extensive swamps exist in this ground moraine area and part of the drainage is northward into the Cloquet River, a tributary of the St. Louis. Stratified sand and gravel in Secs. 5 and 9 suggest some outwash areas.

A prominent esker about 50 feet high extends nearly the length of Sec. 16 in the terminal belt and is cut through near its north end by the headwaters of the French River. A small esker was also noted at the center of Sec. 10. Another is cut through by the French River in the northwest corner of Sec. 27 (Plate 19).

GEOLOGY

As noted above, only a few outcrops are known in this township. Some of these, however, are of considerable importance, for they serve to locate the top of the Duluth gabbro more accurately than has heretofore been possible.

In Sec. 1 the Sucker River flows in a pronounced valley excavated in morainic deposits. About 1000 feet east of the west quarter corner, coarse gabbro with somewhat porphyritic patches and a little red feldspar crops out on the west bank of the river. There is some fluxion structure, and the general aspect is that of the top of the gabbro intrusive as exposed in Duluth. East of the river in the bluff at the south section line are extensive exposures of rhyolite. There is thus no doubt that the top of the gabbro mass passes diagonally across the southwest corner of Sec. 1.

In Sec. 11, about a quarter of a mile north of the southeast corner, is a north and northeast facing bluff. Along the edge is an outcrop about 100 feet long of basalt hornfels with some red rock as irregular stringers.

In Sec. 16, there are several exposures in and near the French River. These are coarse feldspathic gabbro varying to anorthosite. Small ferromagnesian patches are oriented with a strike about north-south and a dip of 75° E. A dike of anorthositic gabbro cuts across the outcrop in the northeast quarter, and in the dike the feldspar crystals are lined up parallel to the wall of the dike.

In Sec. 24, along a road leading to a farmhouse in the SW¼, SE¼, is an outcrop of basalt porphyry (porphyrite) with phenocrysts up to half an inch in length. A porphyritic rock somewhat more like a diabase occurs in the Sucker River near the east line of Sec. 25. South of the northwest corner of the section there is also a large exposure of medium-grained diabase with a little reddish feldspar and long ferromagnesian crystals, presumably hornblende. On the east side of this outcrop is an inclusion of felsite which has dark areas like that better exposed along the south town line in Sec. 34.

Near the center of Sec. 28 is an outcrop of medium-grained diabase with well-developed, roughly columnar joints.

Townships 50 and 51 North, Ranges 16 and 17 West, and Township 52 North, Ranges 14, 15, 16, and 17 West

These townships form the northwest portion of the area and are farthest from Duluth (Plate 4). They were not mapped in detail because of the lack of time. So far as is known, outcrops do not occur in this area because of a very heavy cover of glacial drift. Traverses have been made across these townships in the more accessible portions and the glacial deposits examined. Magnetometer traverses were used to locate the basal contact of the Duluth gabbro with the Thomson slates across T. 52 N., R. 15 W. All of T. 52 N., R. 14 W., and roughly the east half of T. 52 N., R. 15 W., are underlain by Duluth gabbro. The west half of T. 52 N., R. 15 W., and all of Rs. 16 and 17 W., from Tps. 50 N. to 52 N. are believed to be underlain mainly by Thomson slate. The slate was penetrated by drilling for a proposed dam on the St. Louis River near the center of Sec.

34, T. 50 N., R. 17 W. Slate was also encountered at 186 feet in a well near the center of Sec. 11, T. 51 N., R. 16 W.

Throughout this region the glacial deposits are probably between 100 and 200 feet thick on the average. A greater thickness has been penetrated in a few places. A belt of terminal moraine extends southwesterly across the area from T. 52 N., R. 15 W., to T. 50 N., R. 17 W. (Plate 4). Within this belt the topography is somewhat hilly. Most of the remaining area is covered by ground moraine and has a gently rolling topography with boulders abundant at the surface. Locally, nearly level areas of outwash cover the other drift deposits, and the soil is sandy and free from boulders. The southwest portion of T. 50 N., R. 17 W., is a good example, as is a small area around Sunset Lake in T. 51 N., R. 17 W.

Small areas of swamp are characteristic of the region (Figure 2). Most of the streams are sluggish and are bordered by a swamp zone, usually narrow but at places spreading out to a width of a quarter of a mile or more. Other swamps are irregular or round depressions in the general level. This poor drainage is characteristic of a youthful glacial topography where melting ice has left an irregular topography and time has been too short to establish a good drainage pattern by erosion.

CHAPTER IX

ECONOMIC GEOLOGY

Clay Deposits of Wrenshall

The clay deposits at Wrenshall (Plate 6) have been used at brick plants in that vicinity since an early date in the settlement of the region. Winchell in his report on Carlton County in 1899 noted that there were five plants in the vicinity.[1] The clays are more or less typical of the lake clays deposited by Lake Duluth. The total thickness is given by Winchell as 40 feet, of which the lower 30 feet are bluish or gray and the upper 10 feet mainly red. Grout gives the thickness as developed to 50 feet and explored to 80 feet.[2] Varves are conspicuous in some fresh exposures. The pits forcibly remind one that the red lake clays which occur so widely over the area covered by glacial Lake Duluth are red only because they are weathered near the surface.

The clay is high in lime and fairly high in other bases as shown by the analysis given below. The upper red part of the clay also burns red, but the deeper clays, which are gray or bluish gray, burn cream-colored. This

Analysis of Clay from Wrenshall *

	Per cent		Per cent
Silica	48.79	Soda	2.22
Alumina	12.08	Potash	2.05
Iron oxides	4.60	Loss on ignition	12.02
Magnesia	5.54	Moisture	1.26
Lime	12.10	Titanium oxide	.29

* A. W. Gauger, analyst.

difference is apparently a result of leaching of the lime from the upper clay because a high amount of lime tends to counteract the tendency of iron to turn clays red on firing.

Tests show that the clay from Wrenshall cannot be burned to a very low porosity without danger of melting out of shape. It produces a porous but good common brick. In recent years the production of building tile for fireproof walls in large buildings has been emphasized.

Clay similar to that at Wrenshall is widely distributed over the area covered by Lake Duluth (Plate 4). Doubtless other areas could be opened up to produce similar products. Inasmuch as the clay is relatively low grade, further attempts at production would probably meet a severe competitive problem except when building is at a high rate.

[1] *The Geology of Minnesota,* 4:21.

[2] *Clays and Shales of Minnesota* (United States Geological Survey Bulletin 678, 1919), p. 137.

Water Supply

The city of Duluth obtains its municipal supply from Lake Superior at Lakewood (Plate 14). The water from the lake is soft and cold at depth throughout the year. Only occasionally do storms cause the water to become roily. Duluth has as excellent a water supply as any city in the country.

The following data furnished by the city water department applies to the average water in Lake Superior at the city intake at 38° F.

	Parts per million
Ammonia nitrogen	.046
Albuminoid nitrogen	.072
Oxygen consumed	2.7
Total solids residue at 180° C.	54.
Chlorides (Cl)	1.5
Total iron	.10
Free carbon dioxide	2.2
Dissolved oxygen	9.3
Silica (SiO_2)	2.5
Calcium (Ca)	17.3
Magnesium (Mg)	2.7
Sulphate (SO_4)	6.0
Sodium and potassium as sodium	1.4
Total hardness (calculated)	54.

The water supply for the metropolitan area, except that supplied by the lake, is variable and not always sufficient or suitable. The fundamental conditions that govern water supply may be rather simply stated, and these conditions are important to any individual attempting to obtain a supply of water. The main conditions are (1) the thickness and character of the unconsolidated material and (2) the character of the bed rock encountered.

The thickness of the glacial drift and other unconsolidated material varies from zero at the rock outcrops to hundreds of feet in some of the morainic areas. In general the opportunity to obtain satisfactory wells is limited where the unconsolidated material is thin. The difficulties encountered at the Duluth Homestead project are a good example. From two to seven wells were drilled for some of the homes before a suitable supply of water was obtained. Not only is the quantity likely to be limited where the rock ledge is near the surface, but the danger of contamination is greater because the water accumulates along the rock surface and then travels laterally. Where the ledge is near the surface, great care should be used in determining the relative positions of wells to cesspools, stables, and other possible sources of contamination.

The character of the unconsolidated material is also important. A few feet of coarse gravel may, and usually will, furnish an abundant supply of water for a home or farm. On the contrary, no thickness of the plastic red lake clay will furnish a suitable supply. In general, it will be found that rather deep wells are necessary in the lake plain of glacial Lake Duluth, and where the clays lie directly on bed rock no satisfactory supply may be available. As a rule, the terminal moraine deposits are fairly thick and have much gravelly material in the belts, as shown in Plate 4. Wells may usually be obtained at reasonable depths and the supply will be abundant and of good quality. In the ground moraine belts conditions are more variable.

The drift may be thin and not very sandy or gravelly. In that case good water supplies are not readily available. However, if there is a considerable thickness a satisfactory supply is usually available although it may be necessary to drill to some depth to develop it.

Outwash plains are usually sandy and gravelly and normally furnish abundant water at shallow depths.

The rocks of the Duluth area are mainly of igneous and metamorphic origin — that is they either formed by cooling and crystallization of molten material or resulted from recrystallization of other rocks by heat, pressure, and deformation. In either case the rocks are massive, crystalline, and lacking in porosity except where fractured. There is very little opportunity to get water in these rocks and drilling deep wells in them is usually a waste of money. The lava flows found alongshore and inland from Minnesota Point to Two Harbors have porous, vesicular, and amygdaloidal zones at the tops of the individual flows. Therefore, along the shores wells have been developed at places by drilling to these porous zones found at different depths. The main difficulty with these wells is the fact that the water is often hard, has a high alkalinity, and sometimes an objectionable taste due to iron. In general, residents along the shore should have water from new wells analyzed by a competent laboratory to determine if objectionable chemical constituents are present.

It has been common practice to use untreated lake water. When there was little habitation this was no doubt safe, but with the growth of population the lake has been subject to many sources of pollution, and no health authority would sanction the drinking of raw lake water.

RECORDS OF DRILLING

No attempt was made to obtain the records of the innumerable wells on farms and at residences except where special information was desired. There have been holes put down for special purposes that are of considerable interest and are summarized below. The deepest well was drilled to 1507 feet at Shore Line Park before 1889 in exploring for natural gas.

Duluth Deep Well, Short Line Park *

NO.	DESCRIPTION	DEPTH (feet)
1	Red, very fine-grained. Difficult to classify. Too much bematite. Probably flow	231–243

* See N. H. Winchell, *Natural Gas in Minnesota* (Minnesota Geological and Natural History Survey Bulletin 5), p. 31, and *The Geology of Minnesota,* 4:567. The log is somewhat different in the two publications. These notes are from samples examined by G. M. Schwartz, December 1947. The samples are on file in Pillsbury Hall, University of Minnesota.

NO.	DESCRIPTION	DEPTH (feet)
2	Dark gray, some red, green, variable. May be amygdaloid	243–276
	No sample	276–380
3	Much like 243–276 but not so fine-grained. Some epidote and chlorite	380–417
4	Same as No. 3 but dirty	417–448
5	Dark gray, very fine-grained. Looks like slate under petrographic microscope with fragments in oil, but might be fresh, arid, very finely crushed basalt	448–463
6	Mostly looks like vein quartz but some rounded grains. Larger fragments are coarse sandstone	463–468
7	Same, pyritic, limonitic. Coarse sandstone. Puckwunge type	468–473
8	Light gray, soft; difficult to classify even under petrographic microscope. Slate of fine-grained and fresh basalt	473–490
9	Essentially like No. 2. Looks like a flow	490–506
10	Essentially like No. 2. Looks like amygdaloid	506–508
11	Very different, probably slate and fine graywacke or ?	508–511
12	Coarse buff sandstone. Puckwunge type	511–513
13	Crushed quartzose sandstone	513–514
14	Same	514–516
15	Same	516–520
16	Same	520–524
17	Same, coarser plus pyrite	524–528
18	Dark gray, fine-grained. Dirty sample	528–530
19	Dark, epidotic. Looks like basalt flow	530–554
20	Same	554–574
21	Mixed, dark, fine-grained, and red; chloride, epidote, etc.	574–590
22	Very fine but probably the same as 21. Amygdaloid	590–598
23	Highly altered. epidote and chlorite. Probably altered amygdaloid	598–613
24	Probably varies from basalt to amygdaloid	613–619
25	Slate, gray	619–680
26	Slate, gray	680–880
27	Slate, somewhat green	880–1080
	No sample	1080–1170
28	Slate, gray	1170–1175
29	Same	1175–1235
30	Same	1235–1340
31	Same plus vein quartz	1340–1370
32	Slate	1370–1375
33	Slate	1375–1400
34	Slate	1400–1435
35	Slate, brown iron-stained	1435–1437
36	Same	1437–1445
37	Probably graywacke slate	1445–1448
38	Slate, very fine cuttings	1448–1450
39	Slate	1450–1452
40	Slate, finely crushed, probably soft	1452–1454
41	Slate, very finely pulverized	1454–1455
42	Same	1455–1456
43	Same	1456–1457
44	Same	1457–1467
45	Same, more yellowish	1467–1477
46	Same, very finely pulverized	1477–1487
47	Same	1487–1495
48	Same	1495–1500
49	Same, not so finely pulverized	1500–1507

Summary

DESCRIPTION	DEPTH (feet)	THICKNESS (feet)
Drift, etc.	0–100	100
Rock, no cuttings	100–231	131
Flows	231–463	232
Sandstone (Puckwunge type)	463–473	10
Flows	473–508	30
Puckwunge sandstone and conglomerate	508–528	17
Flows	528–613	85
Thomson slate	613–1507	784

Other drill holes with significant information include a diamond drill hole in the St. Louis River at the site of the Minnesota Power and Light Company dam at Fond du Lac. This hole started at an elevation of 612 feet above sea level and penetrated 6 feet of sand and gravel followed by 102 feet of brown sandstone.

A well at the Duluth Steam Plant located at Fifteenth Avenue West on the St. Louis penetrated 265 feet of clay, sand, and gravel. This is important as proof of the great thickness of unconsolidated material beneath the river.

The following wells on the Superior side of the St. Louis River are included because they show the thickness of unconsolidated material. The data is from the Layne-Western Company.

Great Northern Railway Company Yard, Superior, Wisconsin

Well No. 1

DESCRIPTION	DEPTH (feet)
Fill (cinders)	0–2
Sandy red clay	2–4
Red clay (soft)	4–35
Red clay, large showing of very fine sand (soft)	35–70
Brown silty sand, showing red clay (soft)	70–195
Boulders	195
Red clay, showing fine sand	195–224
Boulder	224
Red clay, showing fine sand	224–240
Harder red clay	240–300
Hardpan, small boulders	300–311
Rock, no recovery	311–313
Hardpan and boulders	313–325
Rock cored and used roller bit. Recovered 2 feet. The core shows a red, somewhat conglomeratic sandstone	325–332

Well No. 2

Cinders	0–3
Sand and gravel	3–7
Red clay, soft	7–47
Softer red clay, showing gravel	47–100
Red clay, soft, showing fine sand	100–135
Red clay, soft, large showing fine sand	135–210
Red clay, showing fine sand. Boulders	210–270

DESCRIPTION	DEPTH (feet)
Boulders	135
Boulders	270
Red clay, showing fine sand	270–285
Rock — cored 12 inches. No recovery	285
Red clay	286–319
Rock — cored	319
Red clay, showing fine sand	319–346
Quite hard, large amount fine sand, showing red clay	346–495
Hard red clay, showing fine sand	495–527
Very coarse gravel, small boulders, and some fine sand	527–543
Red clay	543–550
Rock	550

Well No. 3

Cinders, fill	0–1
Red clay	1–26
Red clay, showing fine sand	26–47
Fine brown sand, very loose	47–59
Hard and soft streaks of red clay and sand	59–170
Soft red clay, large showing fine sand	170–330
Very hard hardpan	330–335
Hardpan and boulders	335–339
Soft red clay	339–344
Very hard hardpan	344–345
Hard red clay	345–348
Rock. Used 5⅞-inch rock bit	348–356

Well No. 4

Fill, cinders, red clay, boulders, and sand	0–16
Very hard red clay, showing sand	16–30
Fine sand	30–36
Hard red clay, showing sand	36–40
Fine sand	40–51
Red clay, hard and soft streaks	51–83
Very hard red clay, showing gravel	83–90
Red clay, large showing fine sand	90–135
Very hard red clay, showing sand	135–167
Hard and soft streaks, red clay	167–175
Soft red clay	175–206
Hard red clay and boulders	206–211
Soft red clay showing sand	211–226
Hard red clay	226–250
Soft red clay, showing fine sand	250–290
Very hard red clay	290–368
Soft red clay, showing fine sand, small boulders	368–416
Very hard red clay, small showing fine sand	416–470
Very hard (hardpan)	470–493
Soft red clay, large showing fine sand	493–525
Very soft fine sand. Took 3 feet of 12 pound mud. Flowed for a short while and stopped	525–549
Very hard red clay and fine sand	549–570

Wells at Knife River*

Hans Peterson well	
Glacial drift and lake sediments	5

* Most of these wells are in lava flows, but at the west side of the village intrusive diabase crops out.

DESCRIPTION	DEPTH (feet)
Rock	114
Carl Erickson well	
Rock	225
Cliff Nelson well	
Glacial drift including lake sediments	70
Rock	87
Frank Nelson well	
Glacial drift and lake sediments	70
Rock	32

Wells Near Palmer's Station

At railroad station	
Glacial drift and lake sediments	55
Lava flows	121
Well at farm of J. Hubta	
Glacial drift and lake sediments	45
Lava flows	80
Well at farm of M. Aketh	
Glacial drift and lake sediments	143
Lava flows	59

Wells Near French River

Paul Gilmore well	
Glacial drift and lake sediments	40
Lava flows	152
John Mattson's well	
Glacial drift and lake sediments	26
Lava flows	99
Walter Johnson well	
Glacial drift and lake sediments	10
Lava flows	80
Carl Anderson's well	
Glacial drift and lake sediments	11
Lava flows	110
NW¼, SE¼, Sec. 17, T. 52 N., R. 11 W.	
Red lake clay (water probably at rock surface)	19
NW¼, NW¼, Sec. 9, T. 51 N., R. 12 W.	
Diamond drill hole with continuous flow.	
Lava flows	500
NE¼, NE¼, Sec. 21, T. 52 N., R. 13 W.	
Hardpan (clay)	45
Near center of Sec. 2, T. 52 N., R. 12 W.	
Red lake clay down to rock	7
NE¼, NE¼, Sec. 16, T. 52 N., R. 13 W.	
Glacial drift	9
NE¼, NE¼, Sec. 22, T. 52 N., R. 12 W.	
Hardpan (red clay)	22
SW¼, SE¼, Sec. 27, T. 52 N., R. 12 W.	
Dug well. Red lake clay, rocks at bottom	60
SE¼, SE¼, Sec. 35, T. 52 N., R. 12 W.	
Red lake clay	90
Basalt lava flows	160
Near center of Sec. 11, T. 51 N., R. 16 W.	
Glacial drift	186
Slate and blue clay	56

ANALYSES OF WATER OF THE DULUTH AREA
(in parts per million)

	1	2	3	4	5	6	7	8	9	10
Hardness	33.1	6	4	160	14	58	140	93	160	150
Alkalinity	40.5	160	91	240	200	74	74	97	140	130
Iron	Tr.	2.8	.4	.3	...	2	.18	.07	.48	.17
Chlorides		2.1	45	2.3	1.3	Cl. 7.7	Cl. 17	Cl. 2.5	Cl. 4.8	Cl. .7
Sulphates		8.4	110	4.8	.0	...	...	...	97	39
Fluorides		.2	.6	.2	0.2	Fl. 3.2	Fl. .3	Cl. .05	...	Fl. .15

1. Lake Superior at Two Harbors. Average of analyses in 1924, 1925, 1926, April 1927, June 1927.
2. Knife River, well at Carl Erickson's.
3. Knife River, at post office.
4. Stony Point.
5. Larsmont Store.
6. Cloquet, Well No. 3, 1944.
7. Cloquet, Well No. 4, 1942.
8. Cloquet, Well No. 5, 1942.
9. Carlton, Well No. 1. Filtered 1942.
10. Carlton, Well No. 2. Filtered 1943.

BUILDING STONE AND CRUSHED ROCK

Considering the abundance of outcrops there has been a small production of rock in the Duluth area. The principal quarrying of dimension stone was done in the early days when the red sandstone at Fond du Lac (Sec. 6, T. 48 N., R. 15 W.) met with considerable favor. This rock, along with sandstones in general, lost its popularity, probably in considerable part owing to its porosity, which caused it to become very dark with the absorption of dirt. The quarries have been abandoned for a long time.

The only active quarry in the region at present is on the west slope of Ely's Peak in Sec. 32, T. 49 N., R. 15 W., where the lava flows which lie stratigraphically below the Duluth gabbro have long produced crushed trap rock (Plate 8). This rock makes an excellent concrete aggregate and probably will continue to be used indefinitely unless the costs of production force it into a poor competitive position. Another quarry was operated in the past at Fifty-ninth Street and Franklin, where a large excavation was made in the gabbro.

The future of quarrying in the Duluth area is uncertain. In general, the types of stone available are not those used in large quantities except as crushed rock. Limestone is shipped in from Michigan via Lake Superior to supply blast furnace flux and limestone for the cement plant. No limestones exist in this portion of Minnesota.

There is an unlimited quantity of basalt (trap rock) suitable for crushed rock. The limit would seem to be set by the demand at the price at which it can be quarried and crushed.

The Duluth gabbro intrusive has available an enormous amount of rock that is referred to in the trade as "black granite." The demand for this type of rock is limited, so that establishing a quarry for dimension stone would involve a severe competitive problem. The gabbro is more massive than the basalt lava flows. It is, therefore, more difficult to quarry and crush so that the production of crushed rock may wisely be limited to the basalt, as it is at present. A small quarry in the gabbro existed at Thirteenth Avenue West and Third Street. This could scarcely be operated now because the city has grown around it. The old quarry is of special interest because of the petrographic detail exhibited. Here the red rock (granite) intruded a coarse feldspathic gabbro.

In early days attempts were made to quarry the Thomson slate. One small old quarry site exists just east of the bridge over the St. Louis River, where the road enters Jay Cooke State Park (Sec. 5, T. 48 N., R. 16 W.). Another is located east of the main highway entering Cloquet from the south.

More recently a small quarry was operated in Sec. 1, T. 48 N., R. 17 W., between Carlton and Cloquet, when the buildings in Jay Cooke Park were being constructed by the WPA and CCC in 1939.

In general, the Thomson slate lacks the perfection of cleavage necessary for high grade slate. Some of the more massive material makes large slabs suitable for walks.

Gravel Deposits

Gravel furnishes the cheapest satisfactory concrete aggregate as well as surfacing for gravel and "black top" roads. Deposits are therefore eagerly sought, especially when they are close to the place where needed. Glaciated regions in general furnish considerable gravel and the Duluth area is no exception. Many gravel pits are shown on the detailed maps (Plates 5–19). Many are small, a few large. Perhaps the most extensive are the deposits in Secs. 2, 3, and 10, T. 48 N., R. 17 W., and in Secs. 35 and 36, T. 49 N., R. 17 W. This area is west of Carlton and extends nearly to the south edge of Cloquet. The origin of such extensive gravel deposits at this location is somewhat of a puzzle. There is only a minor terminal moraine belt to the north. It is probable that the excavation of the St. Louis River valley has largely destroyed the moraine representing the ice front from which the water poured out to deposit this gravel outwash.

The most extensive gravel deposits occur in two situations differing in origin. One is a series of beach and alluvial fan or small delta deposits formed along the various beaches of glacial Lake Duluth and its successors. The gravel ridges that occur at many places along the upper beach of Lake Duluth furnish moderate amounts of gravel (Figure 21). Much larger deposits were apparently formed by deposits from streams that poured into the glacial lake and, on having their velocity checked by the lake waters, deposited their load of gravel (Figures 22 and 23). Such is believed to be the origin of the large deposits along Miller Creek on the west side of Enger Park. These consist of stratified sand, gravel, cobbles, and boulders. Miller Creek west of the gravel deposit has swept its immediate valley clear of unconsolidated material above the level of Lake Duluth and deposited the material in the lake at its highest level.

A lower level deposit of similar origin existed in Sec. 9, T. 48 N., R. 15 W., between Fond du Lac and New Duluth (Figures 22 and 23). Much of this deposit was used when the new highway (Number 23) was constructed past the lower edge of the deposit. It extends perhaps 50 to 150 feet above the present level of the St. Louis River. It was probably deposited when the glacial lake waters stood about 150 to 175 feet above the present lake level and the material was carried in by the drainage from the valley of Sargent's Creek. The material ranges from silt to coarse cobblestones. Part of the deposit showed typical delta structure, that is, bottom-set, fore-set, and top-set beds (Figure 22). An interbedded zone at one place consisted of fine yellow silt with well-developed varves or annual layers (Figure 23). The silt was partly eroded and coarse gravel deposited over the silt with bedding at a steep angle. Red lake clay covered much of this deposit.

It is suggested that a favorable place to search for extensive gravel deposits would be along and below the upper beach line shown on the various maps accompanying this report. Many deposits have been found and opened, but others may exist beneath a cover of red lake clay.

Another situation where gravel deposits occur in considerable numbers is within the belts of terminal moraine shown on Plate 4. The terminal and recessional moraine belts are built up at places where the ice front halted for some time as forward movement and melting of the ice were about balanced. Streams poured out of the glacier to deposit gravel knolls, which are called kames. Many small gravel deposits have been opened in these kames throughout the terminal moraine areas. Others doubtless will be found, particularly in the best developed portions of the moraine, that is, where the glacial hills are highest.

There are also a few deposits of sand and gravel formed by streams that flowed under the ice. As each stream died out, it left a channel filled with sediment. As the surrounding ice melted, a long, winding ridge known as an esker was left (Plate 19). The best example of an esker is in Sec. 16, T. 52 N., R. 13 W., along the east side of the French River. This can be followed almost across the section from north to south and is cut in two by the river near the north side of the section. The ridge is fully 50 feet high at places and has a rounded cross section with a narrow crest along which a fisherman's trail winds its way. Gravel is well exposed in a cut on a secondary road along the north-south center line of the section.

Another small esker was noted in Sec. 27, T. 52 N., R. 13 W. This esker is also cut in two by the French River.

There are, undoubtedly, other eskers in the area. They can be depended on to furnish abundant gravel when located.

Titaniferous Magnetite Deposits

The Duluth gabbro normally contains a small percentage of the minerals magnetite (Fe_3O_4) and ilmenite ($FeTiO_2$), often as closely intergrown material forming what is commonly known as titaniferous magnetite. At a few places segregations of these minerals occur and at an early date led to some test pitting in an attempt to develop iron deposits.

One of the locations of the test pits was in Sec. 25, T. 50 N., R. 15 W. (Plate 12). Some of the old pits may be seen just west of the church at the corner of Hermantown and Haines roads. The rock is a dark gabbro, but little magnetite may now be seen. It is probable that the original patches which led to the exploration were small and of no importance.

An exposure of a somewhat greater concentration of magnetite and ilmenite was opened at an early date by a pit between converging roads in the NW¼, SW¼, Sec. 7, T. 50 N., R. 14 W. (Plate 11). The pit is now filled with rubbish, but the dump indicates that almost solid magnetite-ilmenite veins up to 2 inches in diameter cut the coarse-grained gabbro.

In the light of present knowledge there is no reason to believe that any of these deposits have potential value.

Little Knife River Exploration

In 1929 considerable exploration for copper by diamond drilling and by shaft was carried out in Secs. 26, 34, and 35, T. 52 N., R. 12 W., in the valley of the Little Knife River, a tributary which joins the Knife River about a mile above its mouth (Plate 18). The diamond drilling consisted of twenty holes, distributed from a point just south of the northeast corner of Sec. 25 southwesterly to a point very close to the center of the SE¼, Sec. 34. The holes varied from 98 feet to 455 feet in depth.

The following log of Hole No. 3 may be considered typical. Logs of the other holes may be consulted in the Minnesota Geological Survey office.

Diamond Drill Hole No. 3

Near northeast corner, SW¼, SE¼, Sec. 26, T. 52 N., R. 12 E., St. Louis County

DESCRIPTION	DEPTH (feet)
Clay and hardpan	0–20
Brown amygdaloid with coarse amygdules, chiefly of laumontite, becoming sparser. Grain, fine to medium	20–25
Medium-grained amygdaloid ophite, very patchy; half has scattered augites and other half closely spaced scolites and quartz. This material is more gray than red and in places shows evidence of alteration. Some of it looks interesting but is apparently in very narrow bands. There is possibly a little fragmental material cemented by lava	25–30

DESCRIPTION	DEPTH (feet)
Same as last, with abrupt change to next section	30–31.5
Medium-grained, gray-brown ophite with few scattered augites	31.5–35.5
Reddish amygdaloid of fair appearance. Augite amygdules near top and bottom, some coalescence in center, laumontite predominate. Grain, fine at top to medium at bottom	35.5–43
Medium-grained ophite with scattered green amygdules becoming sparser. Color brown, but red streaks due to fine hematite appear where feldspars are bunched together	43–46.5
Medium coarse-grained ophite with a very few amygdules. Color is blotchy due to fine reddish brown hematite in the feldspars. Fine specularite of magnetite and few specks of copper throughout	46.5–50
Same as above, but slightly coarser grained and no amygdules. Becomes a little finer at bottom. Fine specks of copper throughout	50–65
Medium to fine ophite, becoming finer with increasing amygdules of chlorite, quartz, and feldspar. Color of last 6 inches of core is reddish brown and grain is fine	65–70
Copper 14 per cent. First 2 feet of core probably represent section 65–70. Open fracture at 72, about 4 inches across and water nearly all lost	70–75
Patchy amygdaloid with chlorite and laumontite amygdules. Grain of rock is fine to medium. Color is gray-brown with a pinkish cast	75–85
Same as last but looks a little more promising. Some of amygdules show alteration	85–90
Amygdaloid, same color and grain as last section, and amygdules, mostly laumontite, though chlorite increases. Near 95 amygdules, average about ⅛ inch. Specks of copper at .6 and 1.2 in core	90–95
Amygdaloid, somewhat same as last but improving in appearance; last 10 inches of core look fairly good. Many amygdules of quartz and datolite in this section carrying fine specks of copper wherever stringers cut through. Chlorite and laumontite fill all amygdules in first foot of core. Color of matrix becomes more reddish and grain is finer in the better part of this section, but there is very little alteration. Abrupt break at end of section	95–99
Gray-brown ophite with varying numbers of augite and chlorite amygdules, some of which have connecting stringers. Grain increases to medium at center of section and declines to fine again at end. Very few amygdules in last 2 feet. Copper 12 per cent	99–105
Amygdaloid, with rapidly increasing number of chlorite and laumontite amygdules. Color, gray-brown. Grain, medium fine	105–106
Fine-grained, red amygdaloid showing some evidence of flow structure and some alteration. Most of amygdules are laumontite, from 1/16 inch to 1/8 inch, but epidote and other green amygdules increase at finish. This is probably the basal amygdaloid of the flow overlying the fragmental. There are a good many unfilled amygdules. No copper to be seen. No top	106–107.5
Red fragmental amygdaloid showing little alteration. Laumontite still present in many amygdules. No copper showing	107.5–108
Red amygdaloid, very little altered. Some calcite, quartz, and epidote and other green amygdules, but laumontite amygdules up to ¼ inch in diameter make up to 20 per cent of this whole section. Their percentage falls off at the end. This section represents a large fragment in the zone	108–110
Fragmental amygdaloid with one 10-inch fragment. Alteration increases throughout this section to almost the end, when it decreases very rapidly. Laumontite continues throughout in amygdules, but epidote, calcite, chlorite, and other zeolites are more common. Few specks of copper in soft green streak at 113. Three inches of section largely made up of quartz with a pale green color (may be prehnite or some other silicate). This is true fragmental material but is of a kind that has been found to carry little or no copper here	110–114
Fine- to medium-grained trap with many augite amygdules, a few of which are large. Little alteration and increase in grain indicates that amygdaloidal top of flow is passed. Few fine specks of copper occur around the edges of larger amygdules. Some feldspar crystals suggest that flow is porphyrite though these are very few and they may be secondary	114–116.5

In diamond Drill Hole No. 3 the sludge assayed 0.14 per cent copper from 70 to 75 feet and 0.12 per cent copper from 100 to 105 feet.

The shaft is located on the east bank of the Little Knife River not far from the northeast corner of the SW¼, SE¼, Sec. 26. The station of the single level is 106 feet below the collar of the shaft, and drifts extend along the strike of the flows about 80 feet northeast and 100 feet southwest. The strike of the slightly mineralized amygdaloidal zone is N. 32°, 45° E. and the dip 12° SE.

Many assays along the drift show a trace of copper or no copper, but a few others show fractions of one per cent of copper with .32 per cent the maximum. The writer first visited the site in 1931. At that time the dump of the shaft showed considerable amygdaloidal basalt with chlorite, laumontite, calcite, and prehnite as introduced minerals. One specimen of highly altered rock contained a considerable number of fine specks of native copper. The drill core shack had been wrecked and cores scattered around showed much fine-grained ophite with amygdaloidal zones and the minerals noted above in some cores.

The nature of the mineralization revealed in this exploration is much like that found on Keweenawan Point; but, as in all other north shore occurrences discovered thus far, the copper content is disappointingly small and erratic.

In 1947 Mr. Frank F. Grout of the Minnesota Geological Survey visited the area with Mr. G. F. Farrell of Duluth to investigate several copper showings in the general area. His notes are as follows:

"Up Sucker River from the bridge over the old highway [Plate 13], 1000 paces along the stream, is a falls where the water drops about 15+ feet in about 20 feet. Below the falls there is, all across the stream, an outcrop, partly under water, of red sediment about 4 inches thick between amygdaloids. Some pipe amygdules run up about 1 foot above the sediment. It seems to be sandy shale. Sheets of metallic copper follow the joints and bedding. The strike was estimated as N. 40° E. and dip 15±°SE.

"On the main Knife River the course of the stream near the mouth is from the west [Plates 17 and 18]. The auto road goes a very short way. Then one must go up about a quarter of a mile, following the "old" channel (now almost abandoned, since a flood cut a better channel a little way northeast of the old one, for nearly a mile). Some float of red amygdaloid conglomerate carries metallic copper, but most has now been picked up. At the upper end of this stretch where float is scattered, a small outcrop of similar rock occurs in the S.W. bank at water level. The best exposure I saw was about 4 inches thick and ran only about 4 feet along the bank. Nearby exposures indicate that the rock above and below is amygdaloid without much color or mineralization.

"A few places farther upstream there are green copper stained veinlets, up to an inch wide, and Mr. Farrell reports one was 6 inches, but ended abruptly."

Foundation Conditions

One of the serious problems met with in the development of Duluth is the hilly topography and the prevalence of hard rock at or near the surface. Along the St. Louis River a contrary condition exists. Here solid rock occurs only at depth beneath a deposit of sand and clay.

The development of Lake Superior has been treated in some detail in previous chapters. A few features may be recalled in connection with the foundation problem along the river and harbor for such structures as bridges, ore docks, grain elevators, and so on. At some stage the site of the harbor and lower river has been gouged out to great depth. We are not certain as to just how this was done. River erosion, glacial scour, and possibly faulting may all have played a part. In any event scattered wells on both the Duluth and Superior sides show that the unconsolidated material now varies in thickness to at least 570 feet. Much of this material is clay and provides a very unstable foundation. This seems to indicate that the usual method of supporting structures on piling is the only practical way of solving the problem.

Throughout Duluth solid rock shows extensively at the surface and even where it is not exposed it will often be found at a depth of a few feet. The outcrops are shown on Plates 8 and 11. The City Planning Engineer's office has prepared maps showing the outcrops and also the areas where the rock is too close to the surface to provide adequate depth for sewers and water mains. Attempts have been made to zone the city, eliminating from residential development areas where the rock is too close to the surface. This is logical because the cost of putting in water mains and sewers, grading streets, not to mention basements, is excessive to say the least. The rocks underlying the city are hard and massive and therefore difficult to excavate.

When buildings are planned for a given area, proper procedure would require determining the depth to bed rock and then, as far as possible, designing the structure to rest on the rock without much excavation. In planning a home it must be remembered that water mains and sewers must be below the deepest frost penetration, and putting these utilities in solid rock is bound to be expensive.

Another problem arises in connection with the steep slopes. Much of the city, except the highest portions, has a layer of red lake clay covering the rock. This clay when wet is very plastic and tends to slide. It therefore is unwise to place any structure on this clay where the slopes are steep. The tendency for the material to creep downhill is great and may cause much expense. The proper procedure is to anchor foundations to the solid rock beneath the clay if this is at all practical.

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