PHYSIOGRAPHY AND SURFICIAL GEOLOGY OF THE COPPER-NICKEL STUDY REGION, NORTHEASTERN MINNESOTA

By Perry G. Olcott and
Donald I. Siegel

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inch (in)	25.4	millimeter (mm)
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mile (mi)	1.609	kilometer (km)

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PHYSIOGRAPHY AND SURFICIAL GEOLOGY OF THE COPPER-NICKEL STUDY REGION, NORTHEASTERN MINNESOTA

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ABSTRACT

The Copper-Nickel study region lies in the Superior Upland physiographic province and is located approximately 60 miles north of Duluth and 100 miles southeast of International Falls, Minnesota. It straddles the Laurentian Divide, which separates Hudson Bay and Lake Superior drainage. The topography exhibits a southwesterly trending lineation that parallels the strike of southeastward-dipping bedrock units and the southwestward direction of ice movement during Pleistocene glaciation. Both bedrock outcrops and many of the glacial features follow this trend. For this study, the region has been divided into seven physiographic areas based on geomorphic features related to the bedrock surface, glacial deposits, and hydrogeologic significance.

The surficial geology is largely a result of two southwestward advances of the Rainy Lobe of the Laurentian ice-sheet. The Toimi Drumlin Field, the oldest glacial deposit, covers much of the southern part of the region. It is bounded on the north by the Vermilion Moraine Complex, an east-west trending series of terminal and recessional moraines that mark the southerly extent of the second advance of the Rainy Lobe. Thin ground moraine and small outwash deposits occur both within and north of the Vermilion Moraine Complex except in the Embarrass and Dunka River basins where outwash deposits up to 200 feet in thickness fill a deep bedrock valley.

INTRODUCTION

Mining of low-grade copper-nickel ore in the Duluth Complex of northeastern Minnesota has been proposed by mining companies at several sites near the Boundary Waters Canoe Area (BWCA), a Federally designated wilderness area. A regional environmental impact study of the effect of proposed underground and open-pit mines on the associated physical, cultural, and economic aspects of the area is required by the State of Minnesota. As part of the environmental impact study, this report and a companion report on the surface-water and ground-water hydrology of the region summarize a study by the U.S. Geological Survey during 1975-78 in cooperation with Minnesota Environmental Quality Board (MEQB), Regional Copper-Nickel Study Staff and the Minnesota Department of Natural Resources.

The Copper-Nickel Study Region is centered on about 40 miles of the lower contact of the Duluth Complex between Hoyt Lakes and the border of the BWCA (pl. 1). It includes about 1,400 square miles in parts of St. Louis and Lake Counties 60 miles north of Duluth and 100 miles southeast of International Falls, Minn.

The purpose of this report is to describe the physiography and the surficial geology of the region; the geologic framework in which the hydrologic system operates. The information presented herein was developed from logs of wells and core holes, U.S. Geological Survey topographic maps, field observations, and test holes augered during the study. Data from unpublished maps in the files of the Minnesota Department of Natural Resources, the Minnesota Geological Survey, and the U.S. Forest Service also were utilized. These data will provide part of the information for predicting ground-water and surface-water occurence, movement, and availability.

PHYSIOGRAPHY

The Copper-Nickel region lies in the Superior Upland physiographic province, which is characterized as "a submaturely dissected, recently glaciated peneplain on crystalline rocks of complex structure" (Fenneman, 1946).

The Laurentian Divide bisects the region and separates Hudson Bay drainage from Lake Superior drainage (pl. 1).

Numerous wetlands and lakes occur throughout the area. The topography is rolling to very hilly and exhibits a moderate-to-strong southwesterly trending lineation that approximately parallels both the strike of the southeastward-dipping bedrock units and the southwestward direction of Pleistocene glaciation. Both bedrock outcrops and many of the glacial features follow this trend. The land-surface altitude, shown by 10-foot contours on the topographic base, and colorkeyed in 100 foot increments (pl. 1), generally reflects the southwesterly areal trend of major landforms. The local topography in the mapped area ranges from 1,375 feet above mean sea level (msl) along the St. Louis River south of Aurora to 2,015 feet in the east-central part of the region. The total topographic relief is about 640 feet.

The topography is dominated by features related to the bedrock surface and the glacial deposits. For convenience of discussion these geomorphic features are divided into physiographic areas based on topography, surficial geology, and hydrogeologic significance.

The Shallow Bedrock-Moraine Area (A in pl. 1) includes extensive areas in the north-central and northeastern parts of the region and extends in a broad band southwestward to the St. Louis River. Its west edge coincides approximately with the western contact between the Duluth Complex and older rocks. The area is characterized by numerous hills and ridges of exposed bedrock interspersed with peat bogs and wetlands. The major surficial deposit is ground moraine generally less than 10 feet thick. Wetlands cover about 20 percent of the area. Several east-west oriented terminal and recessional moraines cross the area at nearly right angles to the northeast-southwest grain. The moraines rise 50 to 75 feet above the local terrain. Most of the land surface ranges from 1,400 to 1,800 feet in altitude. Drainage patterns are irregular and are chiefly controlled by the bedrock surface.

The Drumlin-Bog Area (B in pl. 1) in the southern and east-central part of the region is the northern extent of the Toimi Drumlin Field (Wright, 1972). These closely spaced, elongate drumlins trend southwestward in an en echelon pattern covering most of the area. Elongate peat bogs lie between the drumlins and cover about 30 percent of the area. The land surface gradually declines from 2,015 feet in the east-central part to about 1,400 feet in the southwest. The drainage is strongly controlled by the interdrumlin bogs and forms a pattern of straight parallel streams draining to the southwest.

The Embarrass-Dunka Rivers Sand Plain Area (C in pl. 1) in the north-central and northwestern parts of the region consists of glacial outwash, ice-contact materials, and some lake sand deposited in a deep bedrock valley. The land surface is generally flat, with about 20 percent being covered by peat bogs or wetlands. Land-surface altitudes range from 1,400 to 1,600 feet. The northern limit is bounded by the northernmost recessional moraine of the Vermilion Moraine. Drainage forms a dendritic pattern of meandering streams controlled by the thick glacial materials.

The Outwash-Moraine Complex Area (D in pl. 1) consists of a series of arcuate, terminal and recessional moraines interspersed with a complex system of irregular ice-contact deposits and small discontinuous outwash plains. The moraines have typical knob-and-swale topography. Small kettle lakes and wetlands are present in the outwash areas. Land-surface altitudes range from 1,500 to 1,800 feet. The drainage forms an irrregular dendritic pattern related to the complex morainal topography.

The Embarrass Mountains-Taconite Mining Area (E in pl. 1) includes the east end of the Giants Range and part of the Mesabi Iron Range. The Embarrass Mountains have as much as 460 feet of relief, rising from about 1,450 to 1,910 feet, and form a long arcuate ridge extending from the western boundary of the region, a few miles north of Aurora, to Birch Lake. The bedrock is at or near land surface in most of the area. Red clayey till, commonly overlying sand and gravel or older bouldery till, covers much of the bedrock. Open-pit taconite mines and waste-rock and tailings basins occur in a narrow discontinuous zone along the south flank of the mountains. Straight streams with steep gradients controlled by the bedrock surface drain the area to the north and south.

The Seven Beaver-Sand Lake Wetland Area (F in pl. 1) is an extensive northeast-southwest oriented wetland, which is the largest peat bog in the region. The area is flat to rolling and has several lakes. Land-surface altitudes range from 1,600 to 1,800 feet. Drainage forms a dendritic pattern.

The Aurora-Markham Till Plain Area (G in pl. 1) lies south of Aurora along the western border of the region. The area is characterized by flat topography underlain by a ground moraine that laps onto the west edge of the Toimi Drumlin Field. The ground moraine contains reddish clay till and an overlying buff calcareous till. The area contains a few small lakes and the manmade reservoir, Whitewater Lake. The land surface ranges between 1,400 to 1,500 feet in altitude. Drainage forms a dendritic pattern, reflecting the regular topography.

Drainage

The Laurentian Divide roughly bisects the region from northwest to southeast (pl. 1), separating drainage to Lake Superior by the St. Louis River from drainage to Hudson Bay by the Rainy River. North and east of the divide, the South Kawishiwi River and Birch Lake roughly parallel the contact of the Duluth Complex and older rocks. Water flows westward and southwestward out of the Boundary Water Canoe Area via the Kawishiwi and South Kawishiwi Rivers. The South Kawishiwi joins the northeastward-flowing Birch Lake System, and then flows northward through White Iron, Farm, Garden, Fall, and Newton Lakes on its way to the Rainy River. The principal tributaries from the southeast, which drain the highland formed on the Duluth Complex, are the Isabella River via Bald Eagle and Gabbro Lakes, and the Stoney and Dunka Rivers. South and west of the Laurentian Divide, the St. Louis River and its principal tributaries, the Embarrass and Partridge Rivers, flow to the west. In the southern part of the region, the southwestward-flowing Cloquet River, Whiteface River and Water Hen Creek also are tributaries of the St. Louis River.

GEOLOGY

Bedrock Geology

The bedrock geology is being studied in detail by the Minnesota Geological Survey, in cooperation with the MEQB, Copper-Nickel Study Staff. Consequently, only a generalized overview is presented in this report as background for discussion of the hydrology of the bedrock units in the second product of this study.

Most of the region is underlain by the Duluth Complex, a large body of dominantly mafic igneous rocks emplaced in late Precambrian time (Weiblen and Morey, 1975). Subsequent erosion has exposed and thinned the complex, which now forms the bedrock surface eastward from the trace of its lower contact with underlying rocks (pl. 1).

A 1,104-foot core hole was drilled into the Duluth Complex by the International Nickel Co. at their proposed Spruce Mine site (T. O. Fritz, written commun., 1975). The sample log shows only slight lithologic variation. The core consists of banded troctolite containing inclusions of hornfels and xenoliths of the Biwabik Iron-formation (middle Precambrian). Thin diabase and norite intrusions cut horizontally across the troctolite at various depths in the core.

A one-quarter split of the core was submitted to the U.S. Geological Survey for emission spectrographic analyses of standard detectable elements. Results were compiled for the entire core at depth intervals of approximately 20 feet. The data show no significant variation or apparent change of percentage of the various elements with depth. (T. O. Fritz, written commun., 1975).

Approximately the lower 1,000 feet of the Duluth Complex is known to be irregularly mineralized at its contact with older rock units. Low-grade copper and nickel sulfides occur in this mineralized zone, which dips 30 to 60 degrees southeasterly (Phinney, 1972). Beginning a short distance east of the contact trace and continuing eastward, the zone is below the depth of currently economic mining. Consequently, mining of the copper-nickel ores will be confined to a narrow band 1 to 2 miles wide along the contact of the Duluth Complex and older rocks.

The Duluth Complex intrudes and overlies older metamorphosed sedimentary rocks of the Mesabi Iron Range sequence (Morey, 1972b) in the southern two-thirds of the region. This middle Precambrian sequence of rocks, from oldest to youngest, is the Pokegama Quartzite, Biwabik Iron-formation and Virginia Argillite. These formations rest on the older low Precambrian Giants Range Granite exposed in the Embarrass Mountains. The Pokagama Quartzite, where present, and the Biwabik Iron-formation form the bedrock surface in a narrow belt on the south flank of the Embarrass Mountains, roughly outlined by the line of open-pit taconite mines (pl. 2). The Virginia Argillite, predominantly slate, forms the bedrock surface west of its contact with the Duluth Complex and south of the Biwabik Iron-formation.

North of the Embarrass Mountains and the contact of the Duluth Complex with older rocks, the bedrock surface consists mainly of granite and metamorphosed sedimentary and volcanic rocks of early Precambrian age (Sims, 1970). Extensive faulting in these rocks has exerted strong control on the shape and location of surface-water features.

Small areas in the eastern part of the region, east of Greenwood Lake and Brimson, are underlain by volcanic bedrock of the upper Precambrian North Shore Volcanic Group (Sims, 1970). This group of rocks has no significant areal extent or hydrologic importance.

Surficial Geology

Most of the surficial materials were deposited by two southwestward advances of the Rainy Lobe of the Laurentian ice sheet. These advances across the Superior Upland have been designated the St. Croix and Automba phases of Wisconsin Glaciation (Wright and Ruhe, 1965; Wright, 1972). The distribution of surficial materials is shown in plate 2. The oldest identifiable deposits are the southwesterly oriented drumlins that constitute the northern extent of the 70-mile-long by 25-mile-wide Toimi Drumlin Field. Wright (1972) estimated that the drumlins were deposited 20,000 years ago during the first advance of the Rainy Lobe in the St. Croix phase of glaciation.

Afer deposition of the drumlins, the Rainy ice front retreated northward, leaving numerous blocks of stagnant ice and glaciofluvial deposits of sand and gravel. These deposits are common in topographically low areas such as the Dunka and Embarrass River basins. Subsequent melting of the stagnant ice left many kettles and other collapse features. Several glacial lakes also may have formed and trapped fine sand and silt in their basins (Winter and others, 1973).

During the Automba phase, the Rainy Lobe again moved into the region. The maximum extent of the ice front is marked by the Vermilion Moraine Complex, the arcuate east-west trending terminal and recessional moraines that cross the central part of the region (pl. 2). The ice truncated the north edge of the Toimi Drumlin Field and left a very thin sheet of bouldery till over much of the bedrock within and north of the Vermilion Moraine Complex. The final retreat of the Rainy Lobe reworked some of the till and deposited additional outwash, ice-contact, and glacial lake deposits. Several eskers trending south and southeastward connect with the moraine fronts and mark the channels of streams flowing beneath the ice (pl. 2).

A third glacial event, the advance from the west of the St. Louis sublobe of the Des Moines Lobe, covered the south-western part of the region from the Embarrass Mountains southward (pl. 2), burying the west edge of the Toimi Drumlin Field (Wright, 1972). This ice deposited a clayey, calcareous reddish-brown to buff till over older Rainy deposits and re-treated without leaving any prominent recessional or terminal moraine. The till is a blend of gray calcareous till characteristic of the Des Moines Lobe and older red tills incorporated by the ice along its path.

Postglacial deposits include alluvium locally transported by streams, and bog deposits, chiefly peat, that have accumulated in many of the ice-block and bedrock depressions. Fine-grained sediments and organic material also occur in many of the stream channels and in numerous kettle lakes in the region.

Lithology and extent of surficial materials

Surficial materials, other than organic accumulations and alluvial deposits, are of glacial origin. Unsorted and unstratified till deposited by ground or end moraines is the predominant sediment type. Localized deposits of ablation till have been mapped by Stark (1977). Ice-contact deposits, outwash sand and gravel, and fine-grained glacial lake silt and sand also are found locally. The distribution of surficial deposits is shown on plate 2.

Drift deposited by discrete glacial advances can be differentiated by overall lithology. Rainy Lobe till is characterized as a red to brown bouldery till (Winter and others, 1973; Stark, 1977) containing cobbles and boulders up to 30 percent by volume in a sandy matrix. Clay found in Rainy Lobe till samples collected southwest of the region is mostly montmorillonite (Winter and others, 1973). Preliminary results of clay analyses from the Filson Creek watershed in the northeastern part of the region indicate that kaolinite and chlorite predominate (D. I. Siegel, written commun., 1977).

Till deposited by the Des Moines Lobe in the vicinity of Aurora is generally sandy and calcareous with mixed-layered montmorillonite and illite as dominant clays (Winter and others, 1973).

Locally, the stratigraphy is more complex where ice-contact or lake sediments underlie younger drift. This especially occurs in the Aurora-Markham Till Plain area, where the Des Moines Lobe overlapped and incorporated older tills and deposited a calcareous, buff-colored ground moraine as a thin cap over older Rainy Lobe drift.

Samples of surficial materials were collected by power auger at 12 sites (fig. 1) for detailed grain-size analyses (table 1). The statistics from these samples, coupled with work by Stark (1977), provide the characterization of major surficial deposits shown in table 2. Both the phi deviation and sorting coefficient are a measure of the degree of sorting, the lower the value, the better sorted the material. Although glacial materials are extremely heterogeneous, grain-size distributions tend to be characteristic of the general type of glacial deposits shown in Plate 2. For example, the histograms (fig. 2) indicate that the till is poorly sorted and contains a wide range of sediment sizes, whereas, the outwash and ice-contact deposits are mostly in the sand and gravel size range.

The large positive skewness for the outwash and ice-contact deposits is a measure of the extent that the size distribution for these deposits is weighted toward coarser particle sizes. The skewed relation is because the fine-grained fraction has been washed out of these water-lain deposits. Hydraulic conductivity of glacial materials is directly correlative with grain size, the better sorted and coarser grained material having the highest hydraulic conductivity values.

Table 1.--Tabulated results of
[Particle-size

Map symbol (figure 1)	Location by township, range, and section	Sampled Depth interval (feet)		Lithology	Clay sizes 0.004	Silt sizes 0.004-0.0625
77-1	T56N,R16W,37,NE	25	30	outwash	6.0	14.4
77-2	T56N,R14W, 5,NW	5	10	ice contact	--	1.6
77-3	T56N,R14W, 2,NE	10	15	outwash	5.3	10.8
77-4	T57N,R13W, 8,SW	5	10	outwash	11.2	13.7
77-5	T57N,R13W,21,NW	0	5	outwash	3.8	1.1
77-6	T60N,R12W,14,NE	5	10	ice contact	3.9	4.4
77-7	T60N,R11W,14,SW	10	15	ice contact	4.5	4.1
77-8	T59N,R12W,2-3,SW	0	6	ice contact	4.8	1.7
77-9	T58N,R14W,21,NE	0	1	till	16.2	19.2
77-10	T57N,R13W,19,NW	0	1	till	12.5	18.6
77-11	T58N,R13W,16,SW	0	1	till	16.5	38.3
77-12	T58N,R13W,13,SW	0	1	till	20.0	28.9

grain size analyses, in per cent by weight
diameter, in millimeters]

Sand sizes: V. fine 0.0625-0.125	Fine 0.125-0.25	Medium 0.25-0.5	Coarse 0.5-1	V. coarse 1-2	Gravel sizes: V. fine 2-4	Fine 4-8	Medium 8-16	Coarse 16-32	V. coarse 32-64
17.1	17.2	8.9	9.6	6.3	6.0	6.7	6.6	1.2	0
1.4	3.8	32.0	24.0	11.4	11.9	10.4	3.5	0	0
13.4	14.1	10.6	9.0	6.0	6.3	7.1	13.2	4.3	0
8.2	11.8	14.9	14.8	8.3	8.7	5.4	2.2	0.9	0
2.9	11.1	31.9	33.4	15.2	1.1	0.3	0	0	0
4.0	8.0	12.5	17.4	18.0	13.9	10.6	7.3	0	0
4.0	5.1	11.5	20.1	20.7	9.3	10.6	10.1	0	0
1.8	5.9	11.2	20.6	17.1	11.7	12.0	9.9	3.2	0
7.2	9.0	7.6	11.6	6.9	5.4	5.5	9.1	2.3	0
8.4	10.5	11.5	10.0	5.9	5.9	5.2	5.2	5.6	0
8.9	8.1	5.2	5.6	2.1	1.8	5.0	5.8	2.8	0
8.3	9.9	7.5	9.4	4.0	4.3	3.0	3.2	1.7	0

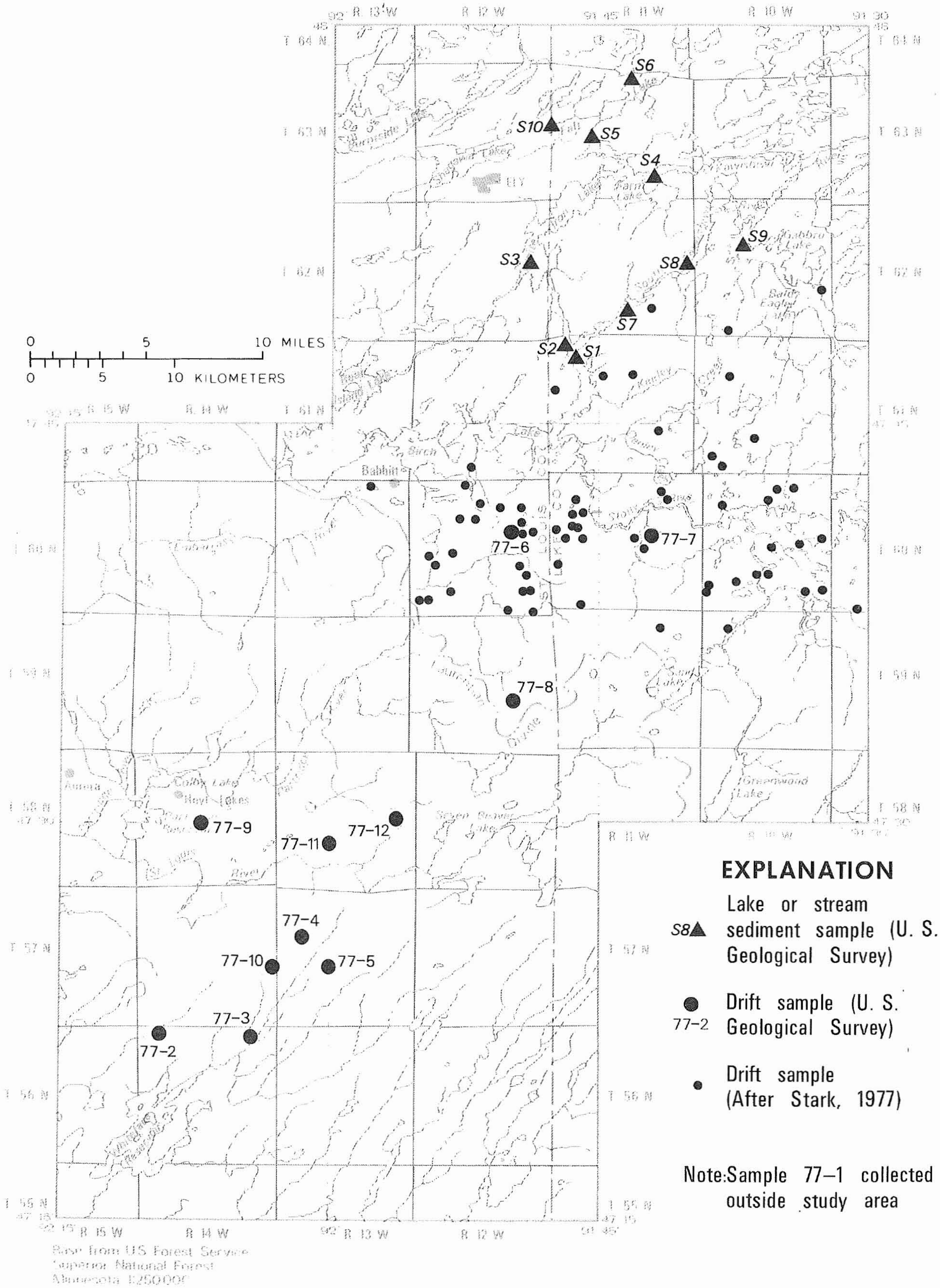

Figure 1.--Sample sites for surficial materials

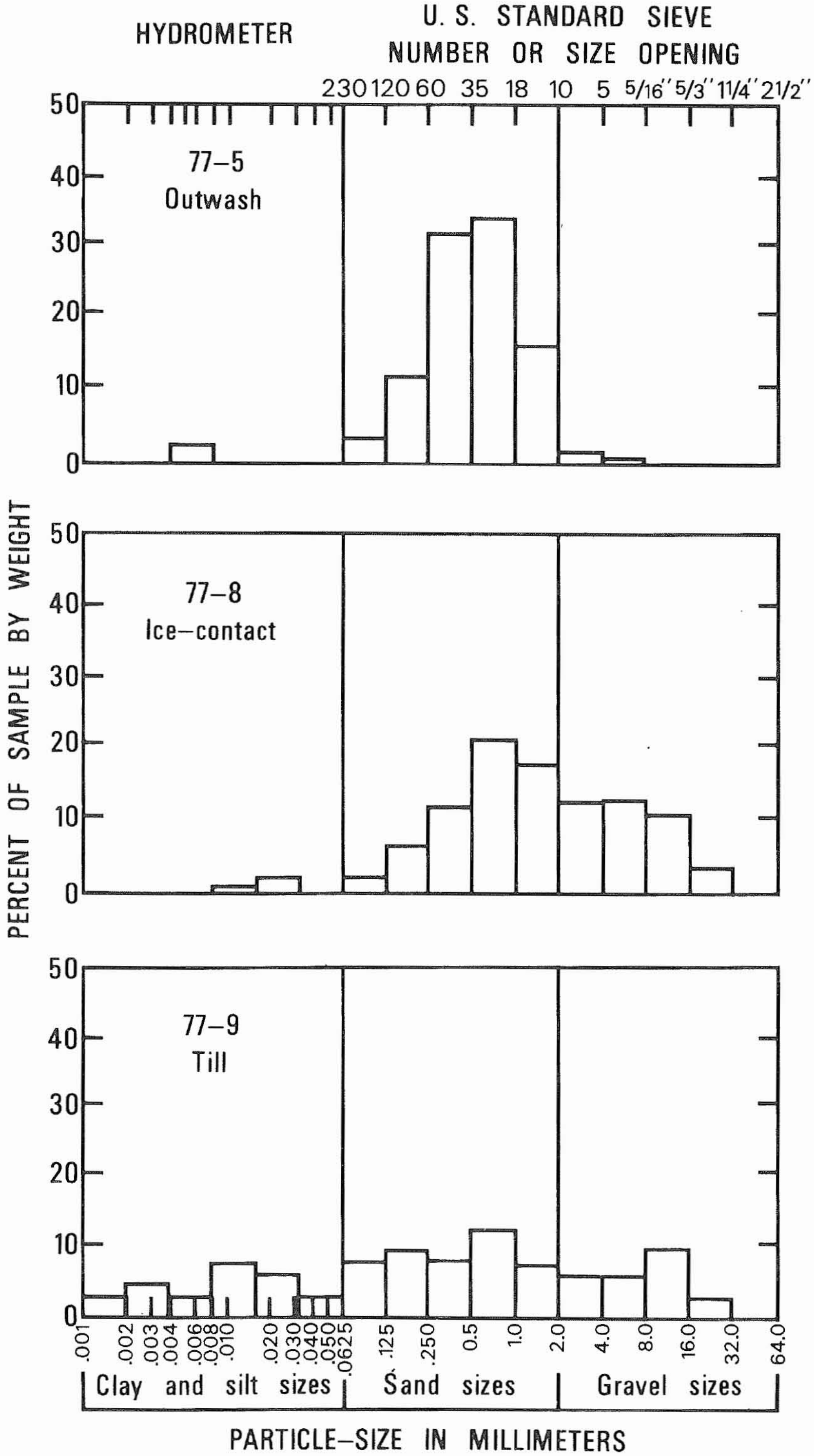

Figure 2.--Particle–size histograms of till, ice–contact, and outwash samples

Table 2.--Statistical summary of grain-size analyses

Unit	Number of samples	Median size (mm)	Inman phi deviation (Φ units)	Sorting coefficient	Skewness	Source
Boulder till	30	0.67	3.5	--	--	Stark (1977).
Red, sandy till	9	.47	3.6	--	--	Do
Bouldery glacio-fluvial deposits	16	.93	2.0	--	--	Do
Red, sandy, glacio-fluvial deposits	32	.87	2.0	--	--	Do
Outwash	4	.35	--	4.0	1.61	U.S. Geol. Survey.
Till	4	.15	--	8.6	0.82	Do
Ice-contact deposits	4	.97	--	2.7	1.25	Do

Where: Median = d_{50}

$$\text{phi deviation} = \frac{\Phi_{84} - \Phi_{16}}{2}$$

$$\text{Sorting coefficient} = \frac{d_{75}}{d_{25}}$$

$$\text{Skewness} = \frac{d_{75} - d_{25}}{[Md]^2}$$

Subscripts refer to the particular percentile of the distribution corresponding to a given diameter expressed in millimeters or phi values (Inman, 1952)

The lithologic composition of the Rainy Lobe drift was examined by Stark (1977) and is shown in table 3 for the pebble-size fraction. Stark reported good agreement between the lithologic composition of the pebble-size fraction and the underlying bedrock. Abrupt changes in lithic types of the drift are apparent across bedrock contacts. Glacial transport of bedrock-derived sediment in some larger grain sizes tends to be for only short distances. For example, gossan-bearing gabbro boulders are confined to a zone extending no more than a mile south of the bedrock occurrence of that material. This may not uniformly be the case for bedrock components in the sand and silt sizes. For these, glacial transport seems to be more persistant, extending for at least 4 miles from bedrock contacts (D. I. Siegel, written commun., 1977).

The trace metal content of unconsolidated materials has not been studied in detail. However, Alminas (1975) found anomalously high values for copper, nickel, cobalt, and silver in the fine fraction of B-horizon soils associated with a known ore body in the Filson Creek area. The metals appear to be held primarily by the clay-size hydrated iron oxides and manganese oxides in which the B-horizon is enriched. Sediment samples were obtained with a 2 inch piston corer from the bottom of lakes and streams between South Kawishiwi River and Fall Lake and were analysed for a suite of metals including copper, nickel, cobalt and mercury. Values are tabulated in table 4 and sample locations are shown in figure 1. No agreement was found between metal occurrence and the proximity of metals to the contact zone between the Duluth Complex and older rocks.

Thickness of surficial materials

The thickness of surficial materials over the bedrock surface of the region is highly variable, ranging from about 200 feet in bedrock valleys to only a veneer over bedrock highs. Because of the complexity of the bedrock topography and the lack of well data, the thickness of the unconsolidated deposits is only generally defined from outcrop, soils, test borings, and available well data (pl. 3). Lines of equal thickness are approximately located and are based to a large degree upon the interpretation of landforms and surficial geology.

In general, the unconsolidated material is thickest in the Embarrass River basin and in the area south of Aurora. The deep, preglacial bedrock valley extending westward from Birch Lake is filled with about 200 feet of glacial sediments (pl. 3), which are partly penetrated by a well 180 feet deep at Babbitt. The basin of the Dunka River was probably a preglacial tributary to the Embarrass River valley, draining through the narrow gap in the Giants Range (pl. 2). Sediments in the Dunka basin are estimated from test drilling to be from 70 to 90 feet in thickness.

The thickness of unconsolidated sediments in the Toimi Drumlin Field probably ranges from 20 to 75 feet. Drumlins 50 to 60 feet high represent the thickest deposits. The area between Seven Beaver and Slate Lakes is estimated to contain from 50 to 100 feet of unconsolidated materials.

Thin unconsolidated deposits, less than 10 feet thick, generally occur on the topographically high areas of the bedrock along the Embarrass Mountains, in a broad belt on the Duluth Complex adjacent to its contact, and in the northern part of the region (pl. 3). Bedrock crops out extensively between the Vermilion Moraine Complex and the Giants Range and in the northeastern part of the region. These areas are characterized by exposed ridges and mounds of bedrock interspersed with small wetlands, which generally contain less than 10 feet of glacial sediment and peat.

Table 3.--Pebble lithologies of Rainy Lobe lithic units
[After Stark, 1977]

Unit	Principal lithologic composition of pebble-size fraction.
Outwash deposits	Principally quartz with lesser amounts of gabbro, granite, iron-formation, greenstone, and metasedimentary rock.
Ice-contact deposits	Principally quartz, gabbro, granite, and minor amounts of greenstone and metasedimentary rock.
Till deposits	Principally granite, gabbro, and iron-formation; some greenstone and metasedimentary rock fragments.

Table 4.--Spectrographic analysis of bottom core
[Concentration, in

Sample field number	Laboratory number	Date of collection	Aluminum	Barium	Beryllium	Bismuth	Boron	Cadmium	Chromium	Copper	Cobalt	Gallium	Germanium
S1	755001	6/12/75	3700	9	0.1	<0.2	3	<1	8	10	8	.5	<.2
S2	755002	6/12/75	2700	20	.2	<.3	2	<1	8	17	13	.3	<.3
S3A	754095	6/11/75	13000	110	.6	<1	23	<4	28	60	30	1	<1
S3B	754096	6/11/75	10000	80	.5	<1	25	<4	28	70	20	2	<1
S4	755003	6/13/75	6300	54	.4	<.5	4	<2	15	20	7	.8	<.5
S5A	755004	6/13/75	6700	80	.3	<.5	8	<2	15	47	8	<.3	<.5
S5B	755005	6/13/75	8800	80	.3	<.7	9	<2	23	70	10	2	<.7
S6A	754097	6/12/75	1800	12	.1	<.2	3	<.5	3	6	5	.2	<.2
S6B	754098	6/12/75	8700	83	.6	<.8	10	<3	35	43	12	3	<.8
S7A	754099	6/12/75	2400	16	.1	<.3	3	<1	7	10	5	.3	<.3
S7B	755000	6/12/75	2700	17	.2	<.3	2	<1	7	10	6	.4	<.3
S8	755006	6/13/75	4300	33	.3	<.4	3	1	25	20	6	.2	<.4
S9	755007	6/13/75	6000	47	.4	<.5	5	<2	15	40	5	.7	<.5
S10	755008	6/13/75	4500	66	.4	<.5	6	2	20	20	7	.6	<.5

[A and B indicate top and bottom slice of core, respectively.]

sediment samples from Kawishiwi River System
micrograms per liter]

Iron	Lead	Lithium	Manganese	Molybdenum	Nickel	Silver	Strontium	Tin	Titanium	Vanadium	Zinc	Zirconium
2800	1	0.8	65	<.2	16	<0.02	8	<0.2	45	5	20	<0.3
4000	2	3	150	<.3	20	.04	7	<.3	65	8	25	<.4
37000	12	6	1400	<1	70	<.1	20	<1	66	34	200	3
38000	10	6	1200	<1	75	.2	20	<1	87	30	240	4
11000	7	8	440	<.5	30	.1	9	<.5	80	13	40	2
10000	25	4	380	<.5	23	<.05	12	<.5	100	20	60	<.7
21000	10	5	340	<.7	20	.2	8	<.7	90	42	50	<1
4200	2	2	150	<.2	13	.03	3	<.2	140	4	15	.3
17000	10	17	550	<.8	57	.1	17	<.8	260	25	80	<1
5400	4	2	200	<.3	12	.04	5	<.3	150	6	20	<.4
5000	2	3	120	<.3	14	.2	6	<.3	230	8	25	<.4
6400	7	4	230	<.4	3	.1	10	<.4	--	100	50	2
8000	5	4	130	<.5	25	<.05	10	<.5	40	15	40	<.7
7700	6	5	350	<.5	35	<.05	17	<.5	120	10	40	6

SUMMARY

The physiography is a reflection of both the topography developed on the Precambrian bedrock surface and the effects of Pleistocene glaciation. Hilly areas reflect either Precambrian bedrock uplands, such as the Embarrass Mountains, or drumlins and terminal and recessional moraines deposited during Wisconsin time. Low-lying surfaces and depressions are related either to similarly low bedrock topography or they occur between depositional features such as drumlins and moraines.

The surficial materials are principally bouldery sandy till and glacial fluvial sand and gravel. These materials can be genetically related to discrete glacial advances and retreats. Peat and clay are interspersed throughout the region in topographic depressions.

The thickness of surficial materials varies greatly and depends principally on local bedrock topography. The thickest deposits are found in buried channels of the Embarrass and Dunka Rivers and in terminal and recessional moraines and drumlins. The thinnest deposits are found in the northern half of the region where bedrock is at or near land surface.

The mineralogy of the surficial materials is generally related to the local underlying bedrock, which was the major source for drift material. Clay mineralogy is variable, with montmorillonite and illite found in the west-central part of the study area and kaolinite and chlorite found in the ground moraines of the Rainy Lobe to the north.

REFERENCES

Alminas, H. W., 1975, Soil anomalies associated with a Cu-Ni mineralization in the South Kawishiwi area, northern Lake County, Minnesota: U.S. Geol. Survey Open-File Report 75-158, 20 p.

Bonnichsen, Bill, 1970a, Geologic map, Allen quadrangle: Minnesota Geol. Survey open-file map.

____ 1970b, Geologic map, Babbitt SW, quadrangle: Minnesota Geol. Survey open-file map.

____ 1970c, Geologic map, Babbitt quadrangle: Minnesota Geol. Survey open-file map.

____ 1970d, Geologic map, Babbitt NE quadrangle: Minnesota Geol. Survey, open-file map.

Eng, M. J., 1976, Rock outcrop and major lineaments in the Copper-Nickel Region south of the Vermilion Moraine: Minnesota Dept. Natural Resources maps.

Green, J. C., Phinney, W. C., and Weiblen, P. W., 1966, Geologic map of the Gabbro Lake quadrangle, Lake County, Minnesota: Minnesota Geol. Survey, Misc. Map M-2.

Griffin, W. L., 1969, Geologic map of the Embarrass quadrangle, St. Louis County, Minnesota: Minnesota Geol. Survey Misc. Map M-6.

Inman, D. L., 1952, Measures for describing the size distribution of sediments: Jour. Sed. Petrology, v. 22, p. 125-145.

Minnesota Geol. Survey, 1970, Reconnaissance geologic map of Ely quadrangle, St. Louis and Lake Counties, Minnesota: Minnesota Geol. Survey open-file map.

Morey, G. B., 1972a, Mesabi Range, in Sims, P. K., and Morey, G. B., eds., Geology of Minnesota - a centennial volume: Minnesota Geol. Survey, Univ. Minnesota, p. 204-217.

____ 1972b, Middle Precambrian, general geologic setting, in Sims, P. K., and Morey, G. B., eds., Geology of Minnesota - a centennial volume: Minnesota Geol. Survey, Univ. Minnesota, p. 199-203.

REFERENCES (Continued)

Phinney, W. C., 1972, Northwestern part of the Duluth Complex, in Sims, P. K., and Morey, G. B., eds., Geology of Minnesota - a centennial volume: Minnesota Geol. Survey, Univ. Minnesota, p. 330-345.

Prettyman, D. H., 1976, Soil survey of the Kawishiwi area, Minnesota: U.S. Dept. Agriculture Forest Service, p. 8-9.

Prettyman, D., and Eng, M. J., 1976, Maps of soil landscape units: Minnesota Dept. Natural Resources, Div. of Minerals, Minesite Data Manual

Sims, P. K., 1970, Geologic map of Minnesota: Minnesota Geol. Survey Misc. Map M-14.

Stark, J. R., 1977, Surficial geology and ground-water geology of the Babbitt-Kawishiwi area, northeastern Minnesota: M.S. Thesis, Univ. Wisconsin, 101 p.

Weiblen, P. W., and Morey, G. B., 1975, The Duluth complex - a petrologic and tectonic summary: 48th Annual Meeting, Minnesota Section, AIME, Minneapolis, Minnesota, 28 p.

Winter, T. C., Cotter, R. D., and Young, H. C., 1973, Petrography and stratigraphy of glacial drift, Mesabi-Vermilion Iron Range area, northeastern Minnesota: U.S. Geol. Survey Bull. 1331-C, 41 p.

Wright, H. E., Jr., and Ruhe, R. V., 1965, Glaciation of Minnesota and Iowa, in Wright, H. E., Jr., and Frey, D. G., eds., The Quaternary of the United States: Princeton, New Jersey, Princeton Univ. Press, p. 29-41.

Wright, H. E., Jr., 1972, Quaternary History of Minnesota in Sims, P. K., and Morey, G. B., eds., Geology of Minnesota - a centennial volume: Minnesota Geol. Survey, Univ. Minnesota, p. 515-547.

U.S. Dept. of Agriculture, 1974, General soil map of Arrowhead Region: U.S. Soil Conserv. Service Inv. Rept.

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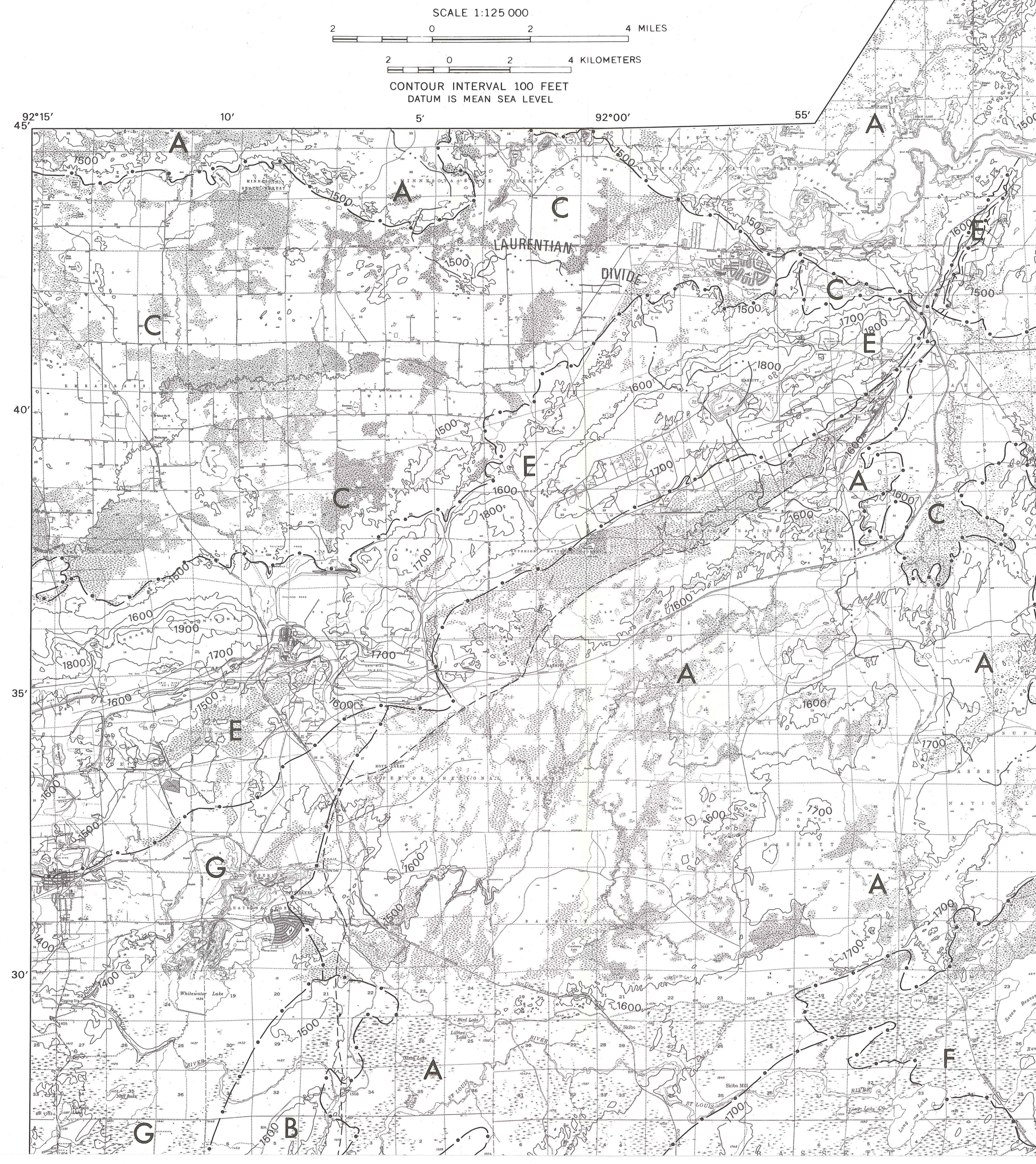

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ENVIRONMENTAL QUALITY COUNCIL

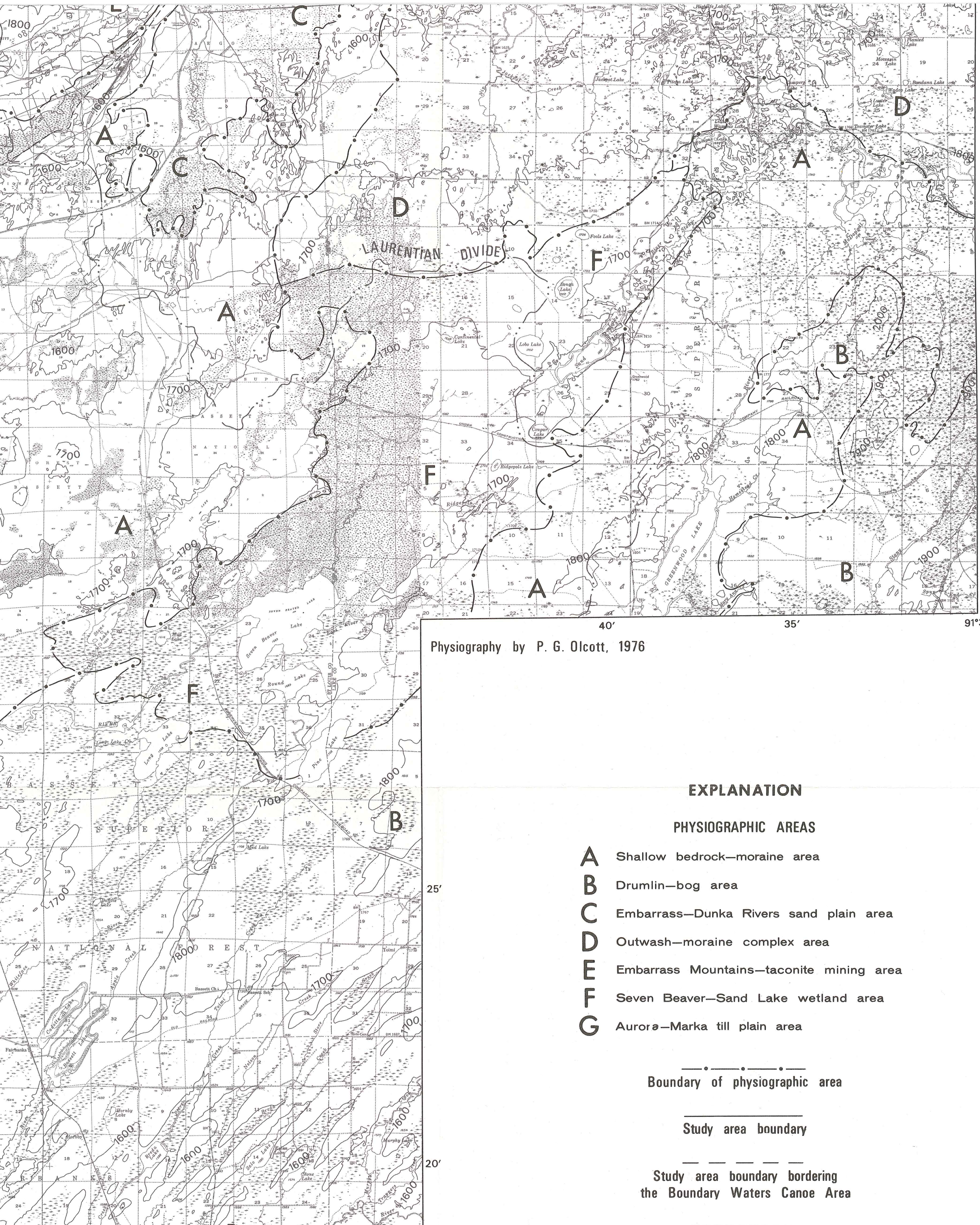
WATER RESOURCES INVESTIGATION 78–51
OPEN–FILE REPORT PLATE 1

Physiography by P. G. Olcott, 1976

EXPLANATION

Base from U. S. Geological Survey
1:24,000 and 1:62,500 quadrangles

PLATE 1.--PHYSIOGRAPHY OF THE COPPER–NICKEL REGIO



Physiography by P. G. Olcott, 1976

EXPLANATION

PHYSIOGRAPHIC AREAS

- **A** Shallow bedrock—moraine area
- **B** Drumlin—bog area
- **C** Embarrass—Dunka Rivers sand plain area
- **D** Outwash—moraine complex area
- **E** Embarrass Mountains—taconite mining area
- **F** Seven Beaver—Sand Lake wetland area
- **G** Aurora—Marka till plain area

—•—•—•— Boundary of physiographic area

——— Study area boundary

— — — — Study area boundary bordering the Boundary Waters Canoe Area

- - - - - - Lower contact and western most extent of the Duluth Complex

OPPER—NICKEL REGION, NORTHEASTERN MINNESOTA

UNITED STATES DEPARTMENT OF THE INTERIOR
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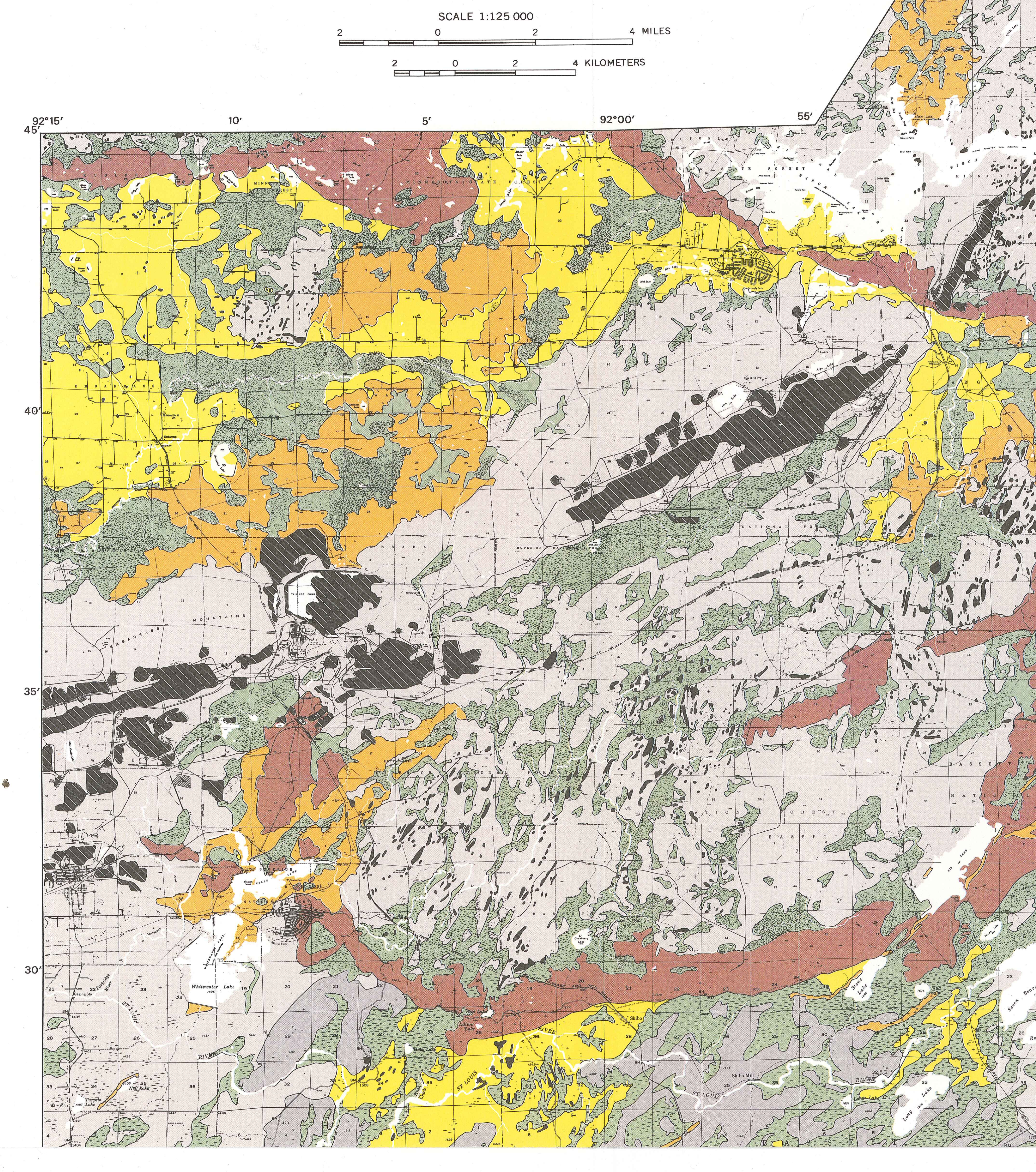

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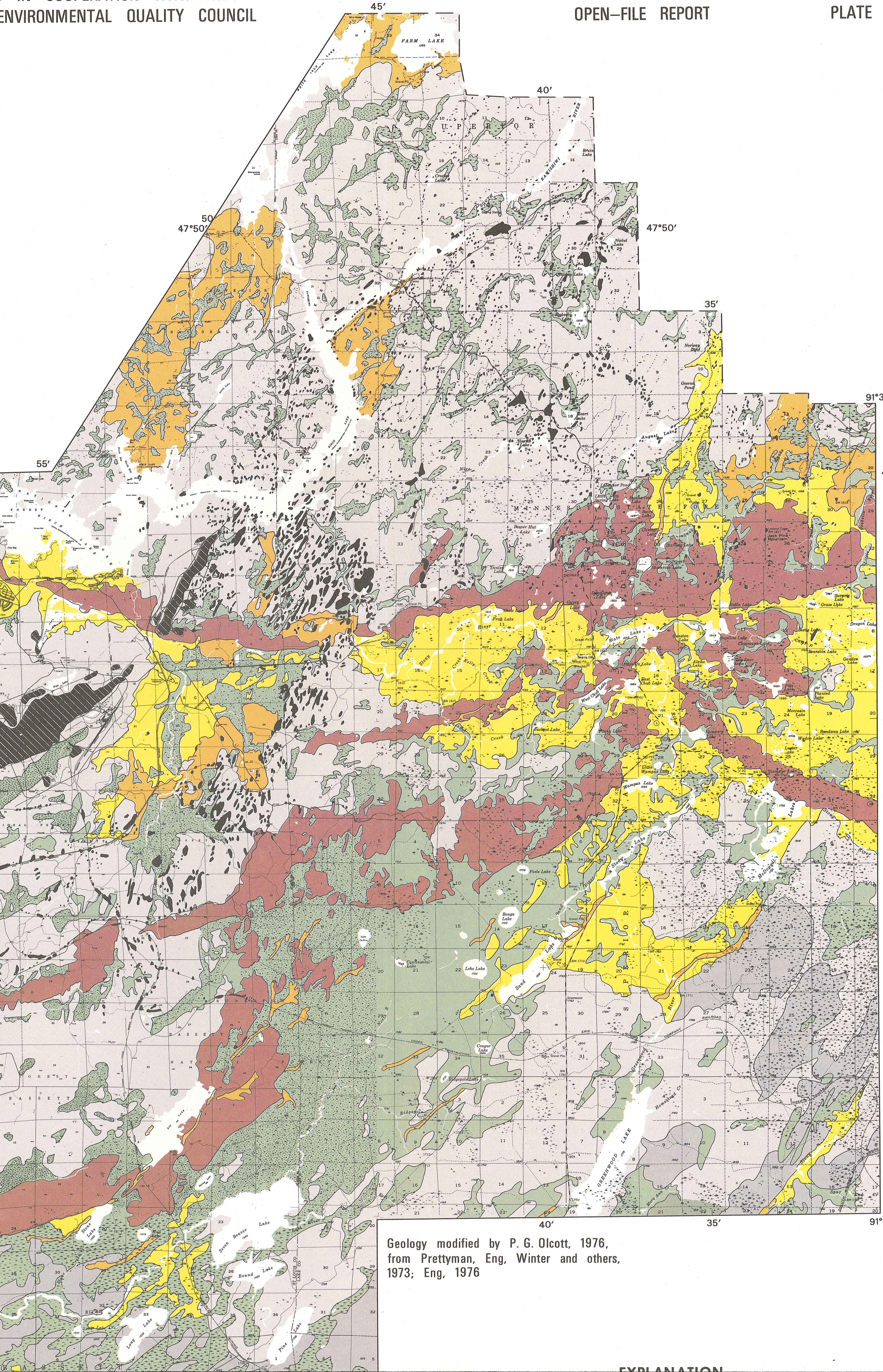
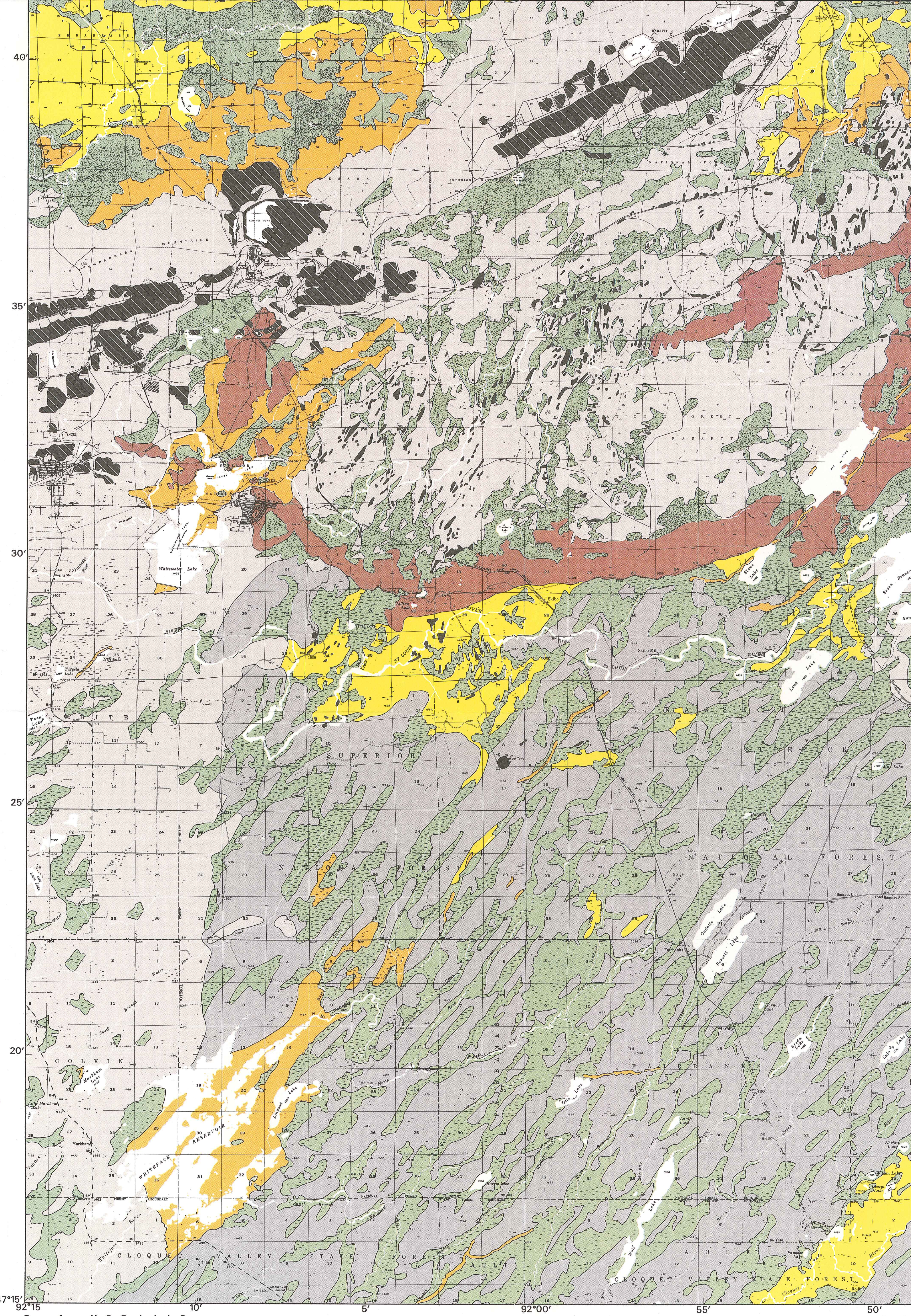
WATER RESOURCES INVESTIGATION 78–51
OPEN–FILE REPORT PLATE 2



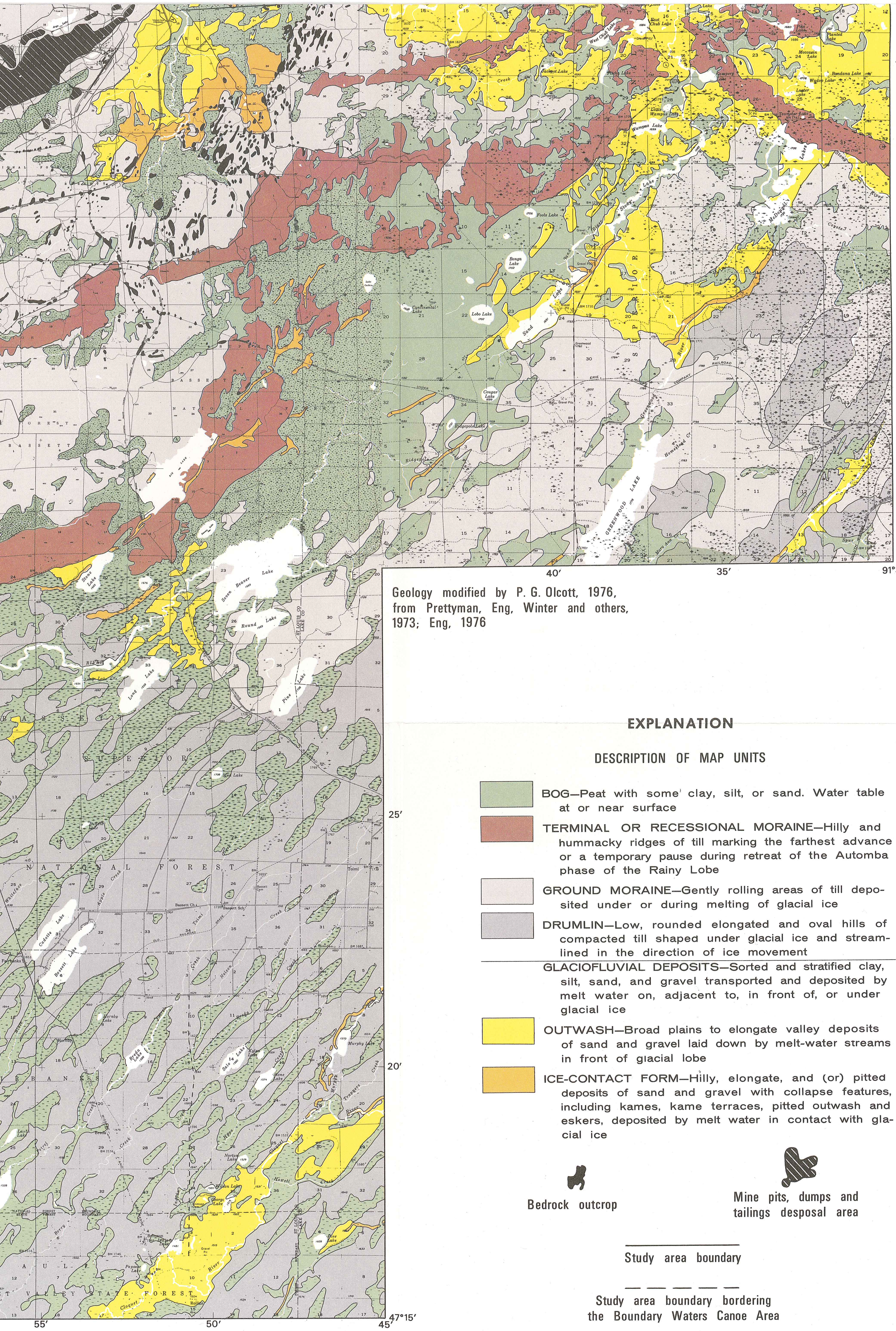
Geology modified by P. G. Olcott, 1976, from Prettyman, Eng, Winter and others, 1973; Eng, 1976

EXPLANATION



Base from U. S. Geological Survey
1:24,000 and 1:62,500 quadrangles

PLATE 2.--DISTRIBUTION OF SURFICIAL MATERIALS IN THE COPPER-



Geology modified by P. G. Olcott, 1976, from Prettyman, Eng, Winter and others, 1973; Eng, 1976

EXPLANATION

DESCRIPTION OF MAP UNITS

BOG—Peat with some clay, silt, or sand. Water table at or near surface

TERMINAL OR RECESSIONAL MORAINE—Hilly and hummacky ridges of till marking the farthest advance or a temporary pause during retreat of the Automba phase of the Rainy Lobe

GROUND MORAINE—Gently rolling areas of till deposited under or during melting of glacial ice

DRUMLIN—Low, rounded elongated and oval hills of compacted till shaped under glacial ice and streamlined in the direction of ice movement

GLACIOFLUVIAL DEPOSITS—Sorted and stratified clay, silt, sand, and gravel transported and deposited by melt water on, adjacent to, in front of, or under glacial ice

OUTWASH—Broad plains to elongate valley deposits of sand and gravel laid down by melt-water streams in front of glacial lobe

ICE-CONTACT FORM—Hilly, elongate, and (or) pitted deposits of sand and gravel with collapse features, including kames, kame terraces, pitted outwash and eskers, deposited by melt water in contact with glacial ice

Bedrock outcrop

Mine pits, dumps and tailings desposal area

Study area boundary

Study area boundary bordering the Boundary Waters Canoe Area

LS IN THE COPPER—NICKEL REGION, NORTHEASTERN MINNESOTA

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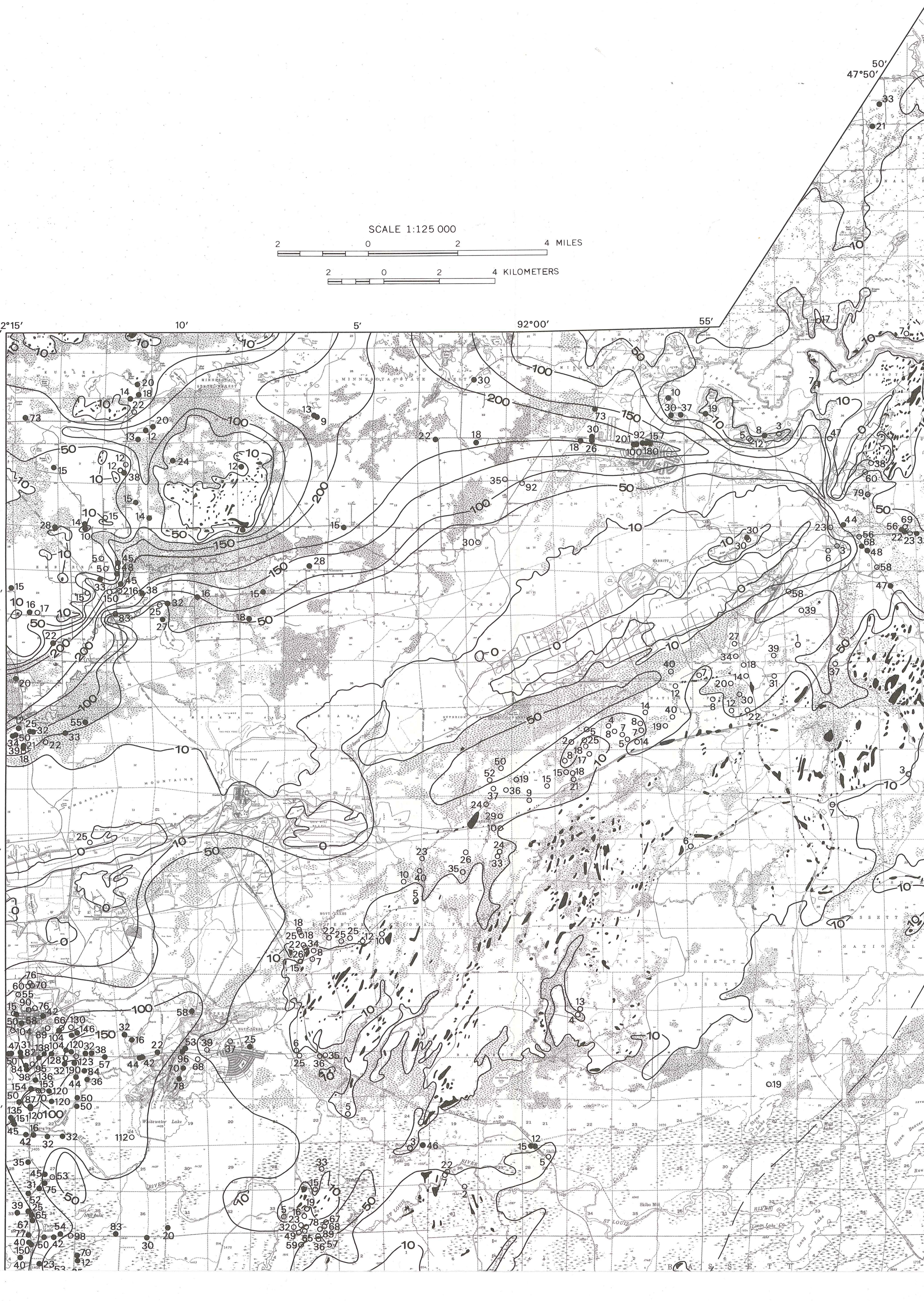
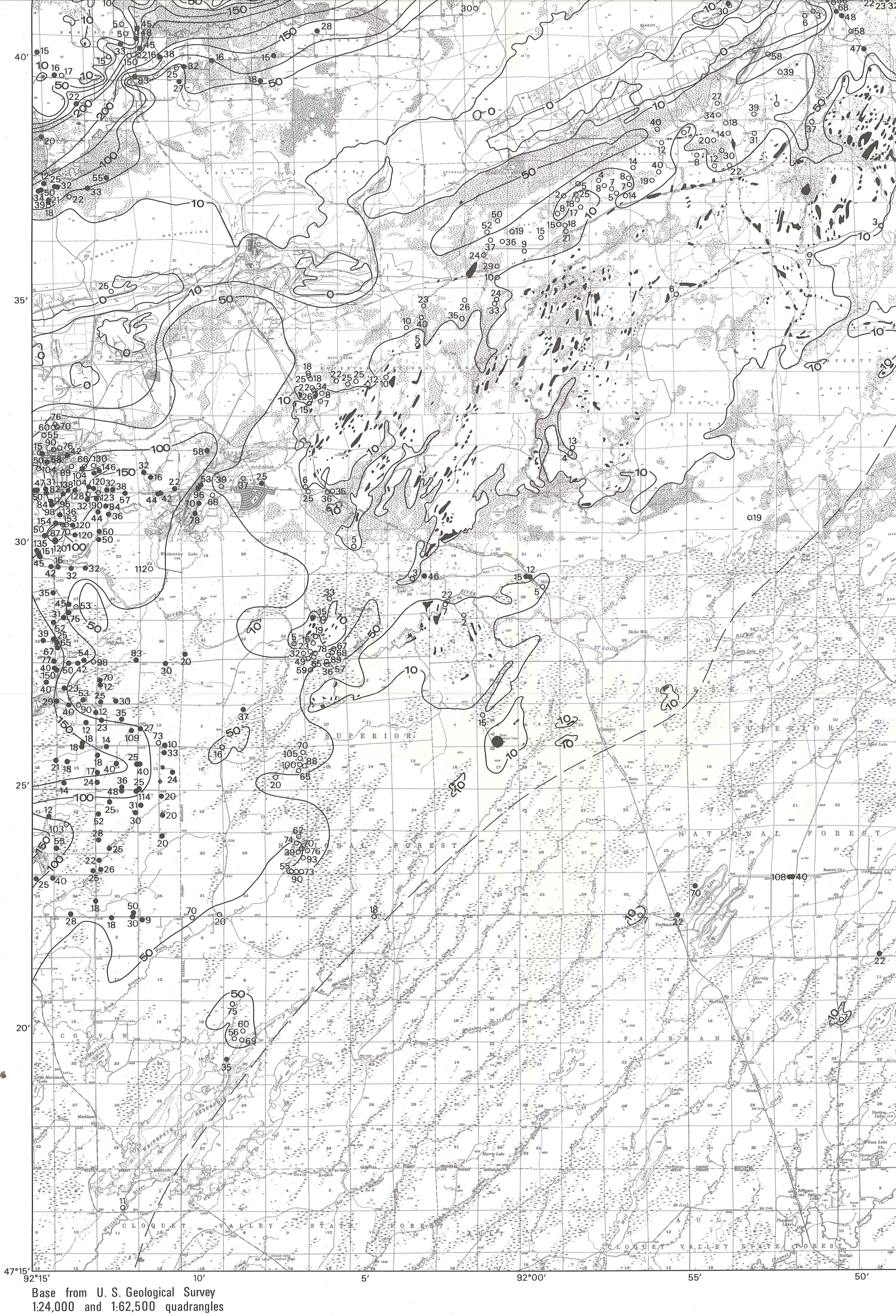


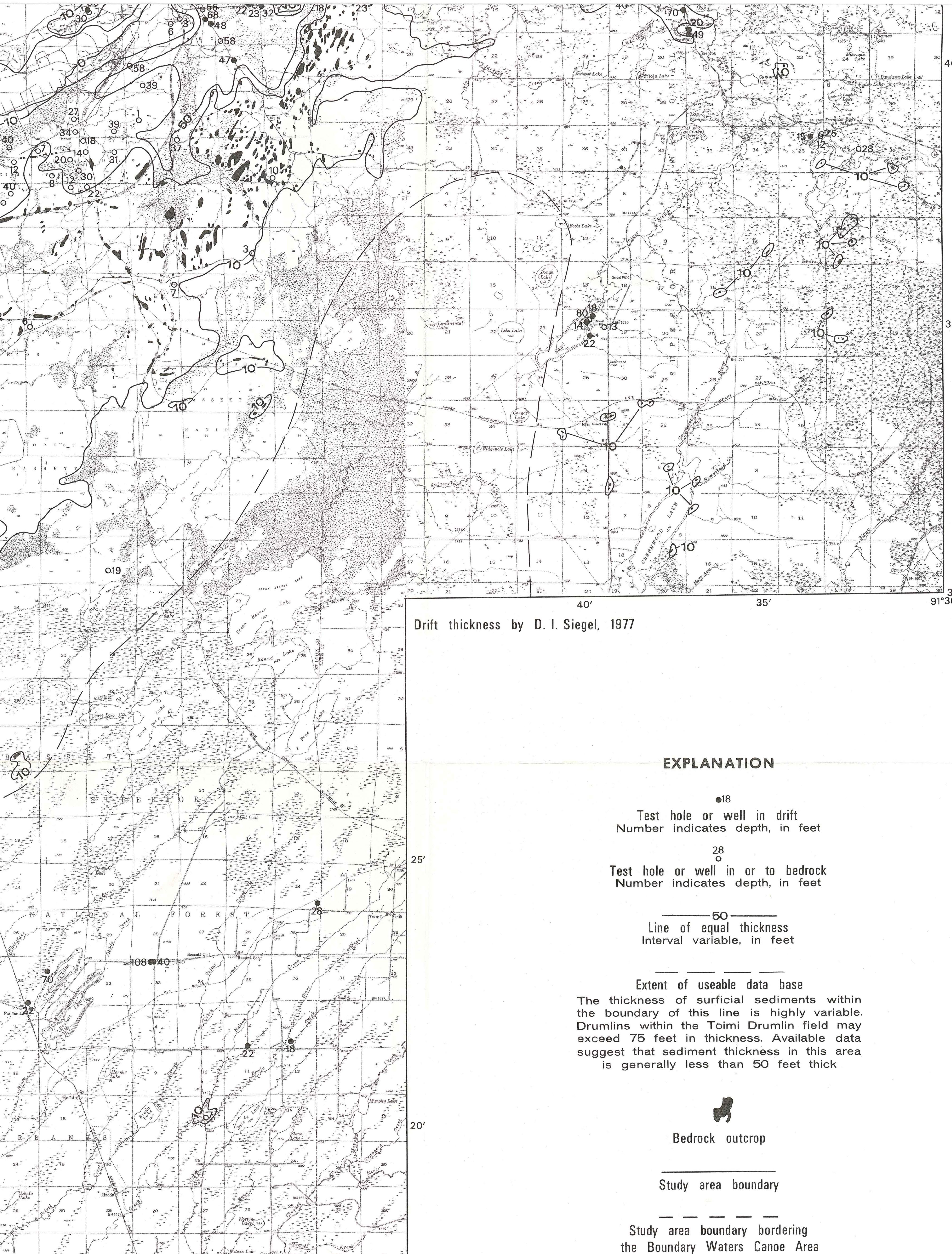
Drift thickness by D. I. Siegel, 1977

EXPLANATION



Base from U. S. Geological Survey
1:24,000 and 1:62,500 quadrangles

PLATE 3.--THICKNESS OF SURFICIAL MATERIALS IN THE COPPER–N



Drift thickness by D. I. Siegel, 1977

EXPLANATION

•18
Test hole or well in drift
Number indicates depth, in feet

28
o
Test hole or well in or to bedrock
Number indicates depth, in feet

——50——
Line of equal thickness
Interval variable, in feet

— — — —
Extent of useable data base
The thickness of surficial sediments within the boundary of this line is highly variable. Drumlins within the Toimi Drumlin field may exceed 75 feet in thickness. Available data suggest that sediment thickness in this area is generally less than 50 feet thick

Bedrock outcrop

Study area boundary

— — — —
Study area boundary bordering the Boundary Waters Canoe Area

IN THE COPPER–NICKEL REGION, NORTHEASTERN MINNESOTA