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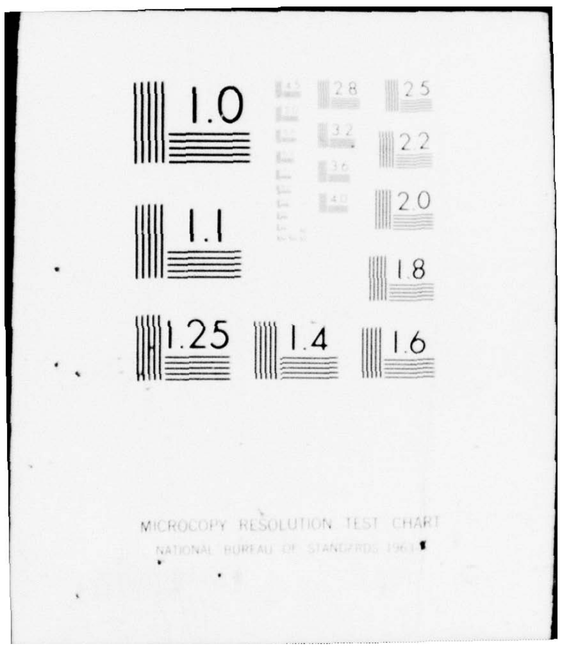
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NATIONAL BUREAU OF STANDARDS 1963

Book 11
Surficial Geologic Data

Seafarer Site Survey
Upper Michigan Region

for
U.S. Navy
Naval Electronic Systems Command
Washington, D.C.

by
EDAW Inc.
under contract to
GTE Sylvania
Communication Systems Division

BOOK 11

SURFICIAL GEOLOGIC DATA of the UPPER MICHIGAN REGION PROJECT SEAFARER

for
U. S. Navy. Naval Electronic Systems Command

by
EDAW, Inc., 50 Green Street, San Francisco 94111

Under Contract to
GTE Sylvania, Communication Systems Division

April, 1976

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In the study area region, near surface materials are primarily separated debris left by the melting of Wisconsin Age glaciers. Because of deposition by glacial ice most of these materials are poorly sorted, ranging in size from clay to boulders. The surficial deposits mantle ranges from a few tens to hundreds of feet in thickness with local outcrops of hard unweathered rock protruding through the cover.

Available geologic data have been summarized on a map which provides information on the location of bedrock outcrops and the areal extent of surficial deposits.

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CONTENTS

SUMMARY

Surficial geology deals with the composition, areal distribution and thickness of soil and rock materials in the uppermost portion of the earth's crust. Within the Study Area, near-surface materials are primarily unconsolidated debris left by the melting of Wisconsin age glaciers, which receded from the area approximately 10,000 to 11,000 years ago. Because most of these materials were transported and deposited by glacial ice, they are poorly sorted, containing particles ranging in size from clay to boulders. A few of the deposits, such as outwash, were deposited by meltwater streams and consist predominantly of well sorted sand and gravels.

The surficial deposits mantle is a highly irregular, glacially scoured bedrock surface, and their maximum thickness varies greatly, ranging from a few tens to hundreds of feet. Locally, outcrops of hard, unweathered rock protrude through the cover of glacial deposits. The glacial deposits are geologically young and have been subjected to the processes of erosion and weathering for only a relatively short period of time and, consequently, stream drainage patterns and soil profiles are still developing.

The Surficial Geologic Data Map was prepared by compiling existing maps and data pertaining to surficial conditions in the Study Area, including maps showing glacial deposits, maps showing the location and size of rock outcrops, drilling logs of water wells, soil borings, etc. (see Validity). The existing maps varied greatly in area covered, scale, and level of detail. Where detailed data were available, such as depth to bedrock from water well logs, this information is shown on the map. Finally, previously unmapped bedrock outcrops and adjustments to contacts between surficial units were added by limited interpretation of small scale color aerial photographs in portions of the Study Area where coverage was available. The map provides useful and reliable information on the location of bedrock outcrops and the areal extent of surficial deposits at the mapped scale. It provides general, but somewhat less reliable, information on the thickness of the glacial deposits.

EVOLUTION

Processes and Time Leading to Existing Conditions

During the Pleistocene Epoch (which began approximately 2.5 million years ago), glaciers advanced and retreated across the Study Area at least four times. Each glacial advance was the result of climatic changes, including longer winters with increased snowfall, and shorter and cooler summers. Because of these changes, a point was reached at the start of each glacial advance where the snow would no longer melt completely each summer, and consequently the snow depth began to increase with each passing winter.

With increased depth, snow compacts under its own weight into a mass of granular ice particles called firn. As the pressure increases, the grains of ice fuse together into a solid mass of ice. Still greater pressure causes the ice to become plastic and flow at a slow rate. Although dependent upon temperature and the slope of the land surface, the thickness of ice necessary to cause it to flow is generally on the order of 100 to 200'. The combination of movement and high pressures that develop at the base of thick sheets of ice (glaciers) enable them to grind or bulldoze away the soil and rock that they cover.

During the peak periods of glaciation, the thickness of the glaciers covering the Upper Michigan region is estimated to have been in excess of 1 mile. These enormous sheets of moving ice removed great thicknesses of rock that once covered the area, and profoundly modified the landscape. Almost all rocks representing the Mesozoic and Cenozoic eras (the last 200 million years) that once may have overlain older rocks still present in the Study Area have been removed. In addition to grinding away the rock, the glaciers left behind extensive deposits of unsorted rock and soil debris as they retreated.

In Upper Michigan, although there were several glacial stages during Pleistocene time, the deposits left by the earlier ice sheets have been totally obliterated. All glacial deposits present in the Study Area are products of the last glaciation, the Wisconsin Ice Age. During this episode of glacial advance, ice fanned out from the Laurentian Highlands (east of Hudson Bay) and advanced southward as far as Ohio, Indiana, and central Illinois. Along with removing earlier glacial deposits, the Wisconsin ice sheets removed more of the pre-existing bedrock, and left behind the surficial deposits which now exist throughout most of the area.

The glaciers left behind an irregular bedrock surface with isolated rock knobs, gently rolling smooth surfaces and fairly deep canyons. This irregular rock surface is covered by a mantle of unconsolidated debris which varies in thickness from a few feet in some places to several hundred feet in others, with isolated areas of protruding bedrock. The melting of the glacial ice resulted in various depositional environments, including meltwater streams, lakes, ice tunnels, and the receding ice itself. These distinctive modes of deposition resulted in certain types of landforms and glacial deposits such as drumlins, moraines, lake plains, and outwash.

Figures 1 through 6 are graphic representations of the last retreating ice sheet. In each drawing the approximate boundary of the Study Area is shown. The figures aid in visualizing the formation of the present Great Lakes and the time relationship of the retreating ice sheet. Figures 7 and 8 illustrate the depositional environments of the various types of glacial deposits and the associated landforms.

Since the retreat of the Wisconsin glaciers approximately 10 to 11 thousand years ago the glacial terrain has been modified only slightly. During this relatively short interval of geologic time, climatic conditions have become more moderate, drainage patterns have developed, erosion has taken place, and soil horizons have begun to develop on the glacial deposits. Because of the short time span involved in terms of geologic processes, landforms and drainage patterns are generally in an immature state of development.

Anticipated Future Conditions

Under present climatic conditions, erosion will continue, and landforms, surface drainage patterns, and soil horizons will develop to a more mature state. However, these processes will take thousands of years, and very little geologic change in the present environment will occur within the next few hundred years. Man's activities appear to be the only factor that can significantly alter the present geologic environment within the immediate future. Activities such as increased farming, mining, and urban development could locally increase the rates of erosion.

16,000 YEARS AGO

FIGURE 1

14,000 YEARS AGO

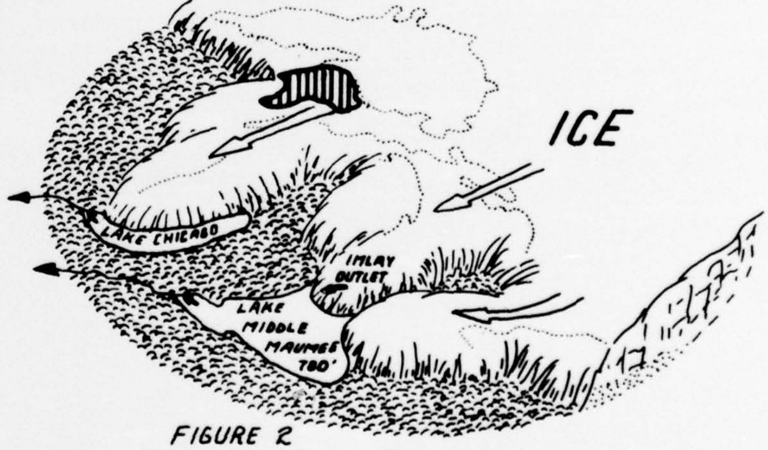
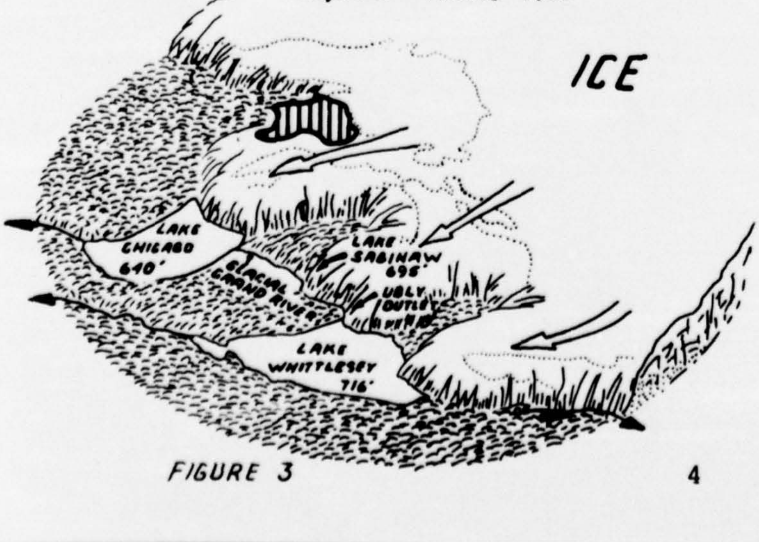


FIGURE 2

12,500 YEARS AGO




Study Area

FIGURE 3

11,000 YEARS AGO

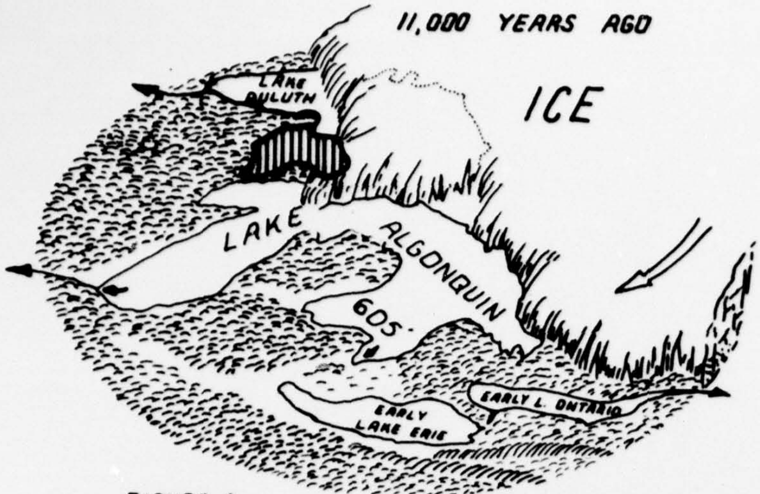


FIGURE 4

9,500 YEARS AGO

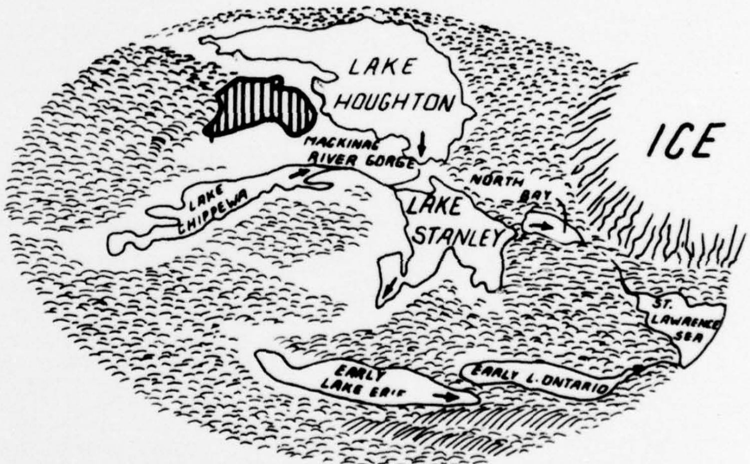
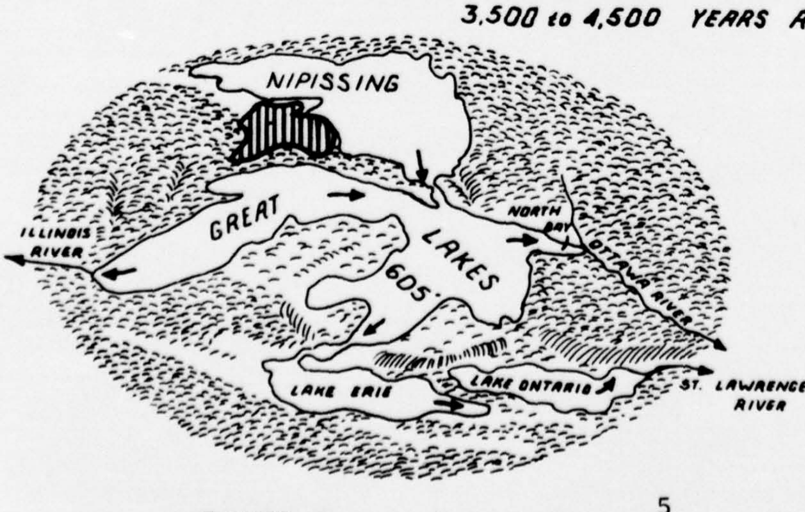


FIGURE 5

3,500 to 4,500 YEARS AGO



 Study Area

(KELLY & FARRAND, 1967)

FIGURE 6

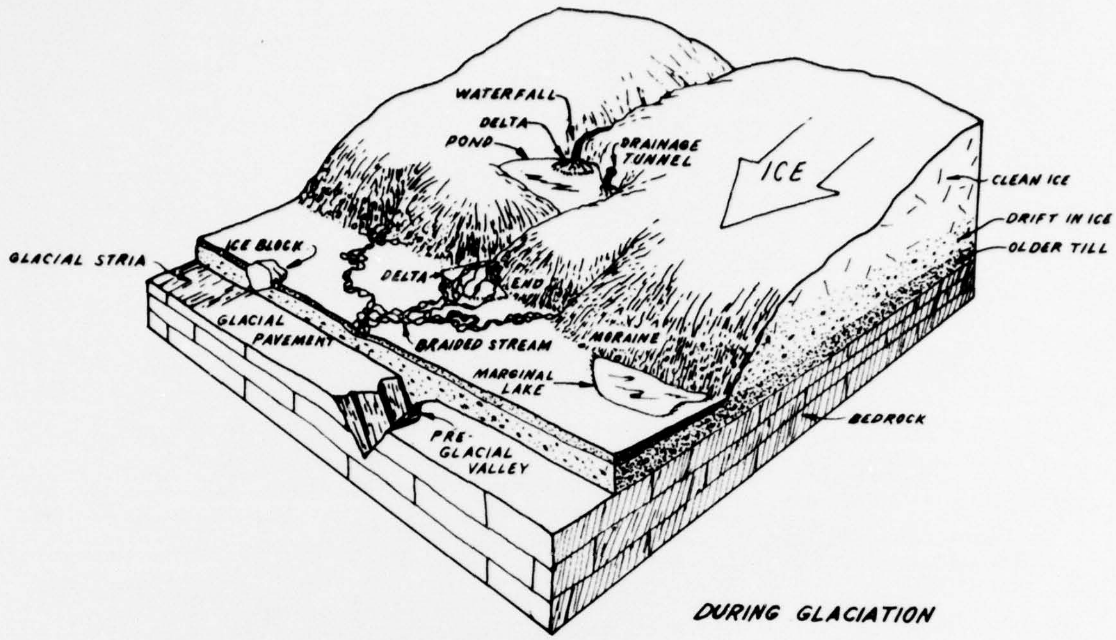
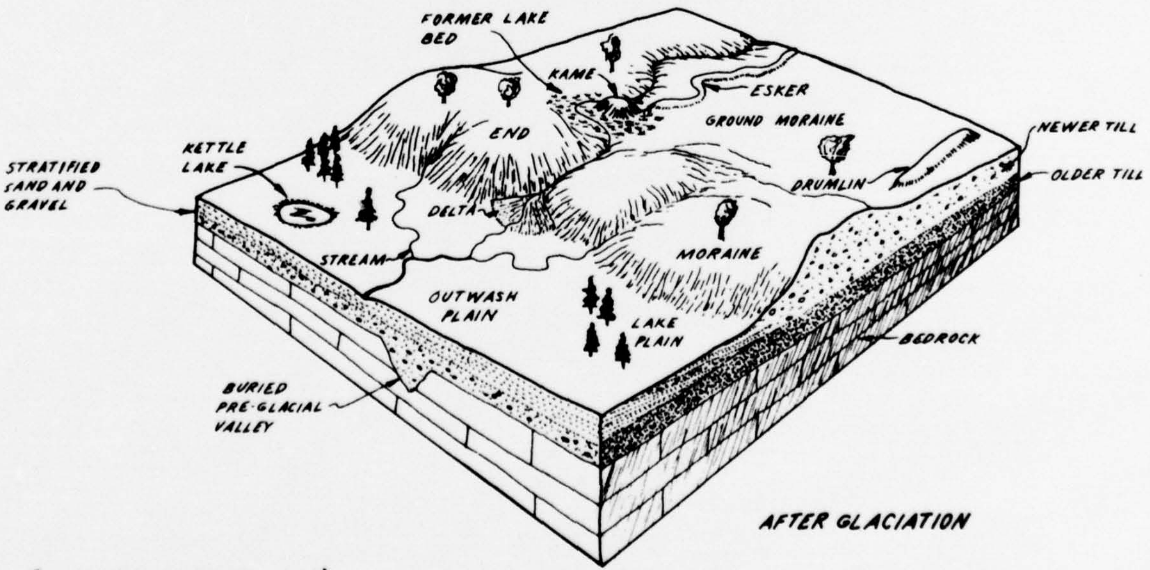


FIGURE 7 FEATURES ORIGINATING AT A GLACIAL FRONT



(KELLY AND FARRAND, 1967)

FIGURE 8 LANDFORMS OF CONTINENTAL GLACIATION

DISTINCTIVE UNITS AND CHARACTERISTICS

Eight distinctive units are shown on the Surficial Geologic Map. This map was compiled from published and unpublished maps at various scales, water well log information, private pipeline plan-profile sheets, and stereo pairs of aerial photographs. The purpose of the Surficial Geologic Data Map is to provide information that can be used to determine the physical properties, depths or thickness of unconsolidated deposits, and areas of rock outcrops. Where the depths of surficial deposits are shallow, the physical properties of the bedrock should also be considered, and the Bedrock Geologic Data Map should be consulted to determine what type of rock is present. It should be emphasized that, while the Surficial Geologic Data Map is specific in showing known areas of rock outcrops and depths to rock where they are available from water well data, it is very general in considering thickness of glacial deposits over large areas, and should be used accordingly.

A detailed description of the units shown on the Surficial Geologic Data Map follows (also see Figures 7 and 8):

T--Till

Till is deposited directly by and underneath a glacier without subsequent reworking by meltwater from the glacier. It is comprised of a heterogeneous mixture of soil materials and rock fragments ranging in size from clay particles to boulders a few feet in diameter. It does not possess any characteristics of a water-lain sediment, such as size sorting, stratification, or absence of fine particles. Because of the poor sorting and clay content, the till generally exhibits low permeability. Till is one of the most widespread surface deposits in the Great Lakes Region. Generally, the thickness of till in the Study Area is a few tens of feet; however, in some localized areas, it may extend to depths of 300'. Local areas of bouldery till present problems in trenching and ripping operations.

M--Moraine

One of the most prominent of continental glacial features is the unique hilly terrain left after the glacier's retreat. These systems of hills, called moraines, are traceable for miles across the landscape. Most of these moraines originate at a stabilized front of an active glacier, where the

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U.S. Navy
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Washington, D.C.

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SURFICIAL GEOLOGY

A / M	Geologic Unit / Geologic Contact
7	Depth to Bedrock (See Text)
BR	Bedrock Near Surface (See Text)
BR	Exposed Bedrock
D	Drumlin
M	Glacial Moraine
T	Glacial Till
O	Glacial Outwash
Lp	Lake Plain
A	Alluvium

forward movement of ice equals the melting rate. In such a situation, large quantities of ground-up rock material melt out of the ice and are deposited in ridges parallel to the ice front, called an end moraine. End moraines form long, relatively continuous hills that are tens to hundreds of feet high. Isolated areas where bouldery materials are concentrated present excavation problems.

The area adjacent to the end moraines in the direction of glacial retreat may be characterized by gentle, rolling terrain. This type of topography is often referred to as sag and swell. These areas are underlain by till, which some investigators have termed ground moraine. Because these deposits are relatively thin, they are not properly moraine, and the current trend is to define them as till.

D--Drumlin

A drumlin is a low, smoothly rounded, elongated, oval hill or mound of compact glacial till. Drumlins are built up under the ice and shaped by its flow, or carved out of an older moraine by readvancing ice. Their long axes are oriented in the direction of ice movement, and they are generally 10 to 100' high and less than one-half mile long. Drumlins are sometimes found in groups of hundreds of aligned oval hills. Groups of drumlins are shown on the Surficial Geologic Data Map. Because the contour interval of the topographic base map is 50', only those drumlins with relief greater than 50' are indicated by the topographic contours. Smaller drumlins are shown on the map, but appear to have no correlation with topography because of the large contour interval.

O--Outwash

As the name implies, this type of deposit is literally washed out beyond the glacier front by meltwater. It is characteristically coarse grained, fairly well sorted, and relatively free of fines. Variations in grain size from place to place are great, however, and the particle sizes present may range from boulders to sand. Very coarse sediments were generally deposited near the ice front; finer sands and silts were laid down farther out on the outwash plain. Characteristically, outwash deposits contain very little clay. The clay stays suspended in the meltwaters and is transported much farther away from the ice than the heavier particles. Because of this lack of fine particles and sorting of the coarse particles, the porosity and permeability of outwash are much greater than till, and it is normally an excellent ground water aquifer (refer to Subsurface Water Data report). Most outwash deposits are tens of feet thick, but some are hundreds of feet thick in local areas.

LP--Lake Plains (Lake Bed Deposits)

Where the ground surface sloped down toward the melting ice front, the meltwater would collect and form a lake ahead of, and in contact with, the ice margin. These lakes became the settling ponds for fine sand, silt, and clay particles. The lake plains which resulted have characteristically flat topography and are often wet and swampy because of poor surface drainage and low permeability of the underlying materials.

A--Swamp Deposits and Recent Alluvium

Swamp deposits and recent alluvium consist of sand, silt, clay, peat, and much which have accumulated in low areas since the retreat of the glaciers. Topographic expression is generally flat and level or gently sloping. Both the composition and thickness of these deposits are extremely variable, and material types and depths at specific locations are determinable only by sampling and drilling. These deposits occur along streams and in low areas dispersed randomly throughout the Study Area. The general wet nature of these materials presents construction problems for most types of facilities.

Br--Bedrock

The Br unit represents areas in which rock outcrops or near-surface bedrock are known to occur, but in which detailed data were not available to permit mapping of individual outcrops. In such areas, bedrock exposures may occur locally, but the total number of rock outcrops probably make up less than 50% of the total area. In the remaining 50% of the areas bedrock is generally at a depth of at least 6'.

Br_1--Bedrock

Where detailed information was available from large scale maps, air photos, and gas transmission pipeline excavation records, rock exposures were mapped with greater accuracy. These areas are delineated as Br_1 on the Surface Geologic Data Map, and include rock outcrops and adjacent areas of near-surface rock.

In recently glaciated areas such as Northern Michigan, bedrock is generally unweathered and hard, because the weathered rock has been scoured away by the glaciers. The majority of rock that crops out consists of very hard crystalline granite, quartzites, gneiss, and other metamorphosed rock types of Precambrian age. Flat-lying sandstones, shales, and limestones of Paleozoic age overlie the Precambrian rocks in the northern and eastern portions of the Study Area. These materials are somewhat softer than the Precambrian crystalline rocks, but are still hard, resistant material. All exposed bedrock outcrops should be considered unrippable.

Several long, thin bedrock outcrops arranged in rectangular patterns are shown on the map. These patterns represent rock exposed in roadcuts and not natural outcrops. To show these roadcut exposures at the scale of the base map, their width has been exaggerated.

Other Mapped Information

Well Data

Approximately 1,000 points indicating depths to bedrock are shown on the Surficial Geologic Data Map. These depths were obtained mainly from water well logs and a few mineral exploration borings. Because of the close spacing of many of these data points on the map, it was not feasible to indicate the exact depth to bedrock at each point. Instead, a key number is shown adjacent to each point, which refers to a specific depth interval as indicated in Table 1. A key number that is underlined on the map indicates the total depth of a well or boring which did not encounter bedrock. Because the bedrock surface is irregular, the depths shown are for the specific point shown, and the information cannot be reliably extrapolated.

Table 1. RANGE OF DEPTHS TO BEDROCK IN WELLS OR BORINGS ON SURFICIAL GEOLOGIC DATA MAP

Key Number On Map	Depth Interval in Feet
1	0-5
2	6-10
3	11-20
4	21-40
5	41-60
6	61-80
7	81-100
8	101-200
9	201+

RELATIONSHIP TO OTHER DATA

Relationships that exist between bedrock types and the residual soils that develop over them in unglaciated regions do not exist in Michigan. The bedrock formations of the Study Area are generally covered with a substantial thickness of glacial material. These deposits contain pebbles and boulders of varying rock types transported varying distances. In some areas, a significant fraction of the rock fragments present may consist of bedrock types derived from the local area, but, in general, the composition of these deposits is not a reliable indicator of the underlying bedrock type. The soils present are related directly to the glacial deposits, which are themselves transported. Soils overlying outwash deposits are predominantly sandy at the surface, grading downward to sand and gravel. Soils which have formed over clay-rich glacial till and lacustrine deposits consist of silty loam to loamy clay and are generally thicker than those soils overlying outwash. Soils overlying organic deposits tend to be thick, mucky peat soils.

Surficial geology in the Study Area is, to a degree, related to topography. For example, topographically steep or rugged areas, knobs, ridges, etc., are generally underlain by hard rock such as grainite, with little or no surficial cover. Rolling or gently undulating terrain is mainly underlain by moraine or till. Low plains generally are underlain by glacial lake deposits of significant thickness except for isolated rock knobs or areas where stream channels have eroded down to bedrock.

Surficial geology has definite effects on vegetation and land use. Rough, knobby areas where glacial deposits are thin or absent have little or no soil development that would support a healthy growth of vegetation. These areas of knobby terrain and thin surficial cover tend to be areas of mining activities and related mineral production. The lake plains and hilly moraine areas where surifical cover is thicker, are used locally for crops and pasture.

Surficial geology is related to surface water flow in that infiltration (and consequently runoff) is directly governed by the permeability of the underlying materials. This is directly related to the amount of water available for streams and the development and size of drainage patterns.

Surficial geology is also related to the occurrence of ground water. In areas of hard crystalline Precambrian rocks that are extremely poor water aquifers, total dependence is placed on glacial deposits for supplying ground water. If the glacial deposits are thin over these crystalline rock areas, the production of most wells is poor. Some glacial units are better aquifers than others. Outwash deposits are fairly well sorted, have few clay particles, and therefore tend to have high permeabilities and good water yields. Moraines and tills, on the other hand, are poorly sorted and contain more clay particles, resulting in smaller yields of water to wells.

VALIDITY

General Procedures and Data Sources

The Surficial Geologic Data Map represents a compilation of existing data pertaining to near surface geologic conditions. No original field mapping was involved in its preparation, and photogeologic mapping was limited.

Sources of information included maps and reports by the U. S. Geological Survey, Michigan Geological Survey, mining companies, and individual professional workers. In addition, personal interviews were conducted with personnel from the Michigan Technological University and Michigan Geological Survey who have worked in the area. Detailed information in specific localities, such as depth to bedrock, were obtained from water well logs provided by the Upper Peninsula Office of the Michigan Geological Survey, pipeline plan and profile drawings obtained from the Northern Natural Gas Company, and the Great Lakes Transmission Company, and a drilling program conducted by M.T.U. during the summer of 1973. Most of the rock outcrops shown on the Surficial Geologic Data Map were taken from existing maps of surficial and bedrock geology (see Figure 10). Others were added from photogeologic interpretation of color aerial photographs.

The level of detail of available information was not consistent throughout the Study Area. By referring to the two index maps (Figures 9 and 10), the coverage and the range of scales of the available surficial and bedrock geologic maps used in compiling the Surficial Geologic Data Map can be seen. In compiling the map, detailed information was used where it existed on larger scale maps, and no attempt was made to maintain a consistent level of detail throughout the mapped area.

Data Reliability/Specific Procedures/Limitations

The Surficial Geologic Data Map provides reliable and useful data on the distribution of rock outcrops, and useful but somewhat less reliable estimates of the thickness of surficial deposits. The data were compiled principally from pre-existing maps, which ranged in scale from 1:11,904 to 1:500,000. As a result, the data are more accurate in those areas where large-scale information was available. Where maps of differing scales were juxtaposed, necessary adjustments in contacts were made on the basis of topography or with the aid of aerial photos (where possible). Where aerial photo coverage was available, the photos were used to delineate rock outcrops. Identification of low, rounded bedrock outcrops was difficult in areas of dense forest, and consequently only large rock knobs jutting above the tree tops are shown on the map.

Because of the irregularity of the bedrock surface, the thickness of surficial deposits could be estimated only within broad ranges. Depths to bedrock at specific data points such as water well locations are representative of only the immediate surrounding area, and depths to bedrock where there is no existing information can only be determined by drilling or geophysical surveys at the specific locations involved.

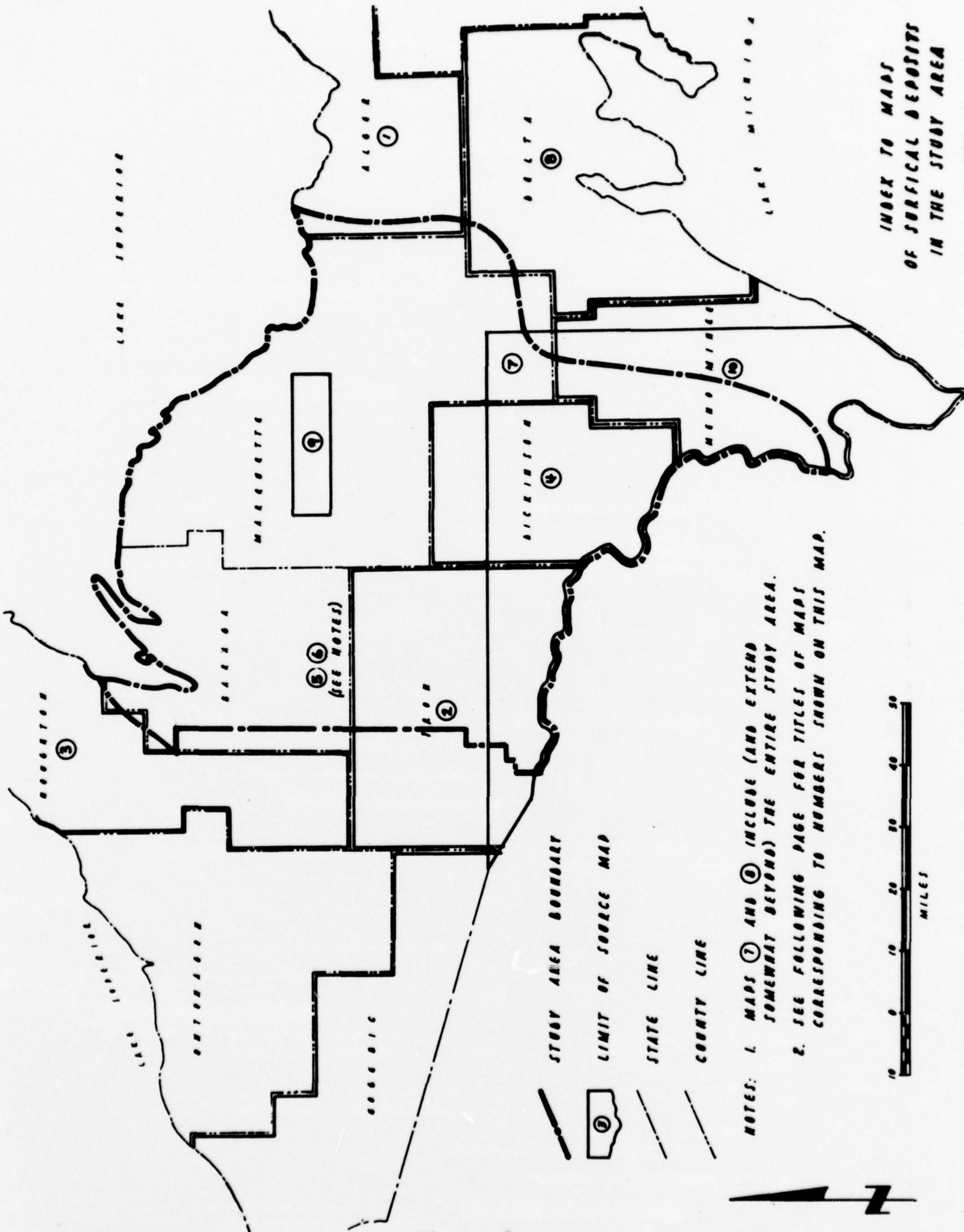
INDEX TO MAPS
OF SURFICAL DEPOSITS
IN THE STUDY AREA
FIGURE 9
LAKE SUPERIOR
LAKE MICHIGAN
ALGER
DELTA
MARQUETTE
DICKINSON
MENOMINEE
BARAGA
IRON
HOUGHTON
ONTONAGON
GOGEBIC
(SEE NOTES)
STUDY AREA BOUNDARY
LIMIT OF SOURCE MAP
STATE LINE
COUNTY LINE
NOTES: 1. MAPS 7 AND 8 INCLUDE (AND EXTEND SOMEWHAT BEYOND) THE ENTIRE STUDY AREA.
2. SEE FOLLOWING PAGE FOR TITLES OF MAPS CORRESPONDING TO NUMBERS SHOWN ON THIS MAP.
10 0 10 20 30 40 50
MILES

Figure 9

INDEX TO MAPS OF SURFICIAL DEPOSITS (Figure 9)

1. Berquist, S. G., Pleistocene History of the Tahquamenon and Manistique Drainage Basins of Northern Peninsula, Michigan; Michigan Geol. Survey, Pub. 40, map of Alger County. Scale : 1" = 4 miles.

2. Doonan, C. J., and Hendrickson, G. E., Surface Geology of Iron County; Map insert in Ground Water in Iron County, Michigan Water Investigation 7, Mich. Geol. Survey, 1967; Geology from S. G. Berquist. Scale: 1" = 2.5 miles.

3. Doonan, C. J., Hendrickson, G. E., and Byerlay, J. R., Surface Geology of Houghton and Keweenaw Counties, from Ground Water and Geology of Keweenaw Peninsula, Michigan, Water Investigation 10, Mich. Geol. Survey, 1970; adapted from Land Type Map, U. S. Soil Conservation Service; Outcrop from USGS Quads; J. P. Hughes Ph.D Thesis, "Physiography of Keweenaw Peninsula"; field studies by Byerlay and Doonan. Scale: 1" = 2 miles.

4. Hendrickson, G. E., and Doonan, C. J., Surface Geology of Dickinson County, from Ground Water Resources of Dickinson County, Mich., Water Investigation 2, Mich. Geol. Survey, 1966. Scale 1" = about 2.4 miles.

5. Leverett, Frank, Surface Geology of Northern Peninsula of Michigan; Mich. Geol. and Biological Survey, Pub. 7, Geol. Series 5, 1910. Scale: 1:1,000,000.

6. Martin, Helen, compiler, Surface Geology of the Northern Peninsula of Michigan, Pub. 49, Mich. Geol. Survey, 1957. Scale 1" = 8 miles.

7. Russell, I. C., Surface Geology Map of Portions of Menominee, Dickinson, and Iron Counties; Mich. Geol. Survey, Annual Report, p. 17, 1969. Scale 1" = 6.5 miles.

8. Sinclair, William C., Surface Geology of Delta County; may included in Reconnaissance of the Ground Water Resources of Delta County, Mich., Progress Report 24, Mich. Geol. Survey, 1960. Scale 1" - about 7 miles.

9. Stuart, W. T., and Rhodehamel, E. C., Ground Water Investigation of the Marquette Iron Mining District, Tech. Report No. 3, Mich. Dept. of Conservation, 1954. Scale 2" = 1 mile.

10. Vanlier, Kenneth E., Surface Geology of Menominee County' map included in Ground Water in Menominee County, Water Investigation 2, Mich. Geol. Survey, 1963. Scale 1" = 9 miles.

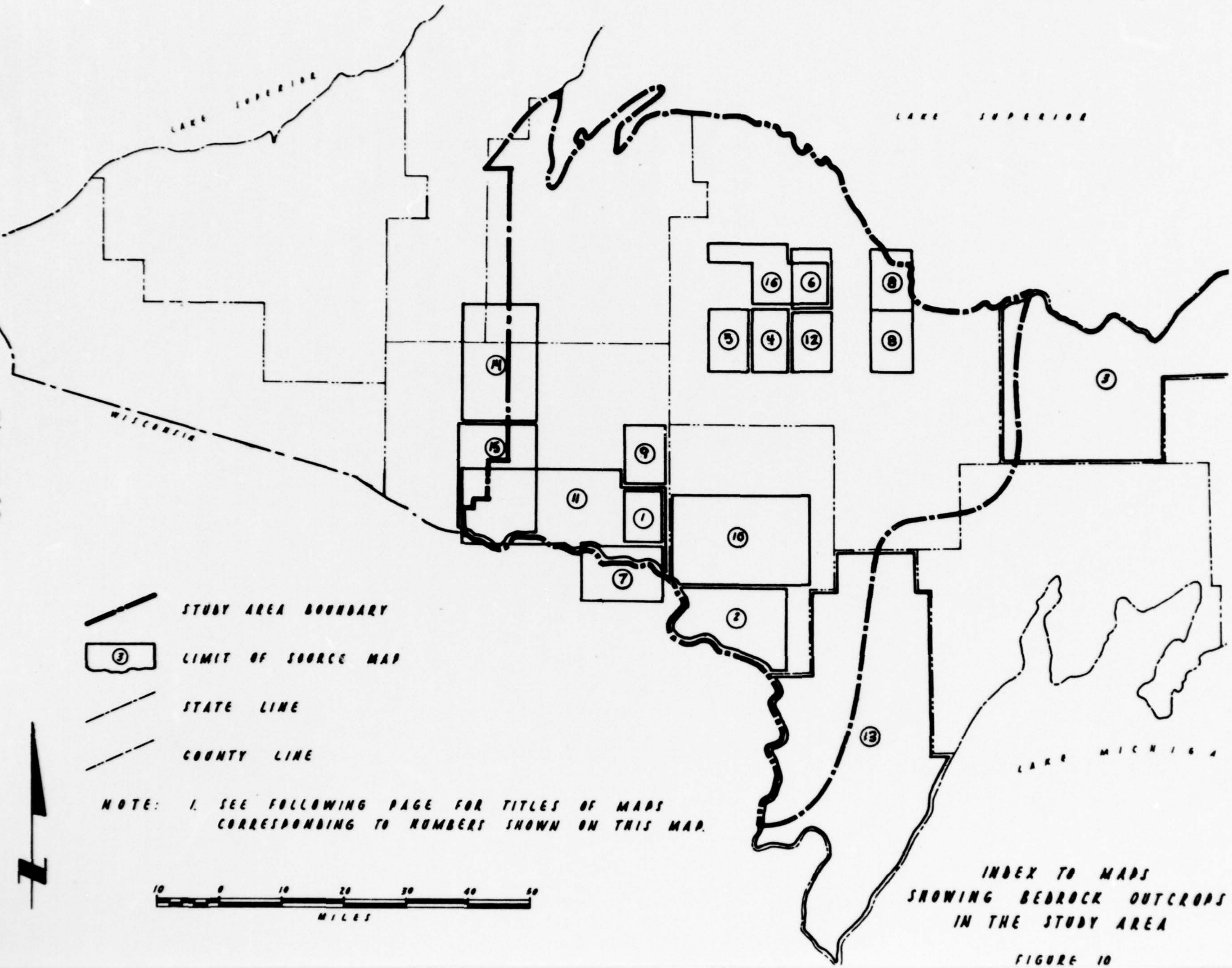
LAKE SUPERIOR
LAKE SUPERIOR
WISCONSIN
LAKE MICHIGA
STUDY AREA BOUNDARY
LIMIT OF SOURCE MAP
STATE LINE
COUNTY LINE
NOTE: 1. SEE FOLLOWING PAGE FOR TITLES OF MAPS CORRESPONDING TO NUMBERS SHOWN ON THIS MAP.
10 0 10 20 30 40 50
MILES
INDEX TO MAPS
SHOWING BEDROCK OUTCROPS
IN THE STUDY AREA
FIGURE 10

Figure 10

INDEX TO MAPS SHOWING BEDROCK OUTCROPS (Figure 10)

1. Batley, R. W., Geology of the Lake Mary Quadrangle, Iron County, Bulletin 1077, 7½ minute Quad. Scale: 1:24,000; 1959.

2. Bayley, R. W., Dutton, C. E., and Lamey, C. A., Geology of Menominee Iron Bearing District, Dickinson County, Michigan, and Florence and Marinette Counties, Wisconsin. Professional Paper 513, 1966.

3. Berquist, S. G., The Pleistocene History of the Tahquamenon and Manistique Drainaga Basins of the Northern Peninsula of Michigan; Michigan Geol. Survey, Publication 40, Series 34, Map of Alger County, 1936, p. 64, Part I, Figure 14. Scale: 1" = 4 miles.

4. Cannon, W. F., Geology Map of Greenwood Quad. 7p minute, Open file map, 1971. Scale: 1:12,000.

5. Cannon, W. F., Republic Quad. 7½ minute NW/4, Open file report, 1971. Scale: 1:12,000.

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APPENDIX A

THERMAL RESISTIVITY DATA

This Appendix presents the results of an office investigation directed at a preliminary evaluation of the thermal resistivity of the soils present in the Study Area.

The thermal resistivity of a soil (ρ) is a measure of the ability of the soil to carry heat away from a heat source such as a buried electrical cable or heat exchanger. A soil with low thermal resistivity conducts heat more rapidly than one with high thermal resistivity. If areas with high thermal resistivity are not recognized and designed against, they can result in overheating and "thermal runaways" of buried heat sources.

The thermal resistivity of a soil depends on a large number of dependent and interdependent soil properties, and consequently is very difficult to estimate consistently and accurately. However, investigations have shown that the primary soil properties affecting the thermal resistivity of a soil are water content, dry density, degree of saturation, and percentage of clay in the soil, and, that by using these parameters, a reasonable preliminary estimate of the thermal resistivity can be made. Direct field or laboratory soil thermal tests are desirable for more accurate values for design of important facilities.

The influence of the above soil properties on thermal resistivity can be expalined by the thermal characteristics of the soil's constituents. Soils consist of a soil grain matrix containing pore spaces filled with air, water, or a combination of the two. Of these three constituents, air has the highest thermal resistivity:

$$(\rho = 4{,}000\ \frac{^{o}C\text{-cm}}{watt})$$

and the individual soil grains have the lowest thermal resistivity:

$$(\rho = 11\ \frac{^{o}C\text{-cm}}{watt}\ \text{for quartz to}\ \rho = 170\ \frac{^{o}C\text{-cm}}{watt}\ \text{for mica})$$

The thermal resistivity of water is:

$$165\ \frac{^{o}C\text{-cm}}{watt}$$

Consequently, the thermal resistivity of a soil depends on the mineral composition, particle size, and degree of compactness of the soil grains (dry density), the quantity of water present (water content), and the relative proportions of water and air in the soil matrix (degree of saturation).

For any given soil, a higher dry density and higher moisture content and degree of saturation yield a lower thermal resistivity. However, as the clay content of a soil increases, the thermal resistivity increases, assuming that other influencing factors such as dry density and moisture content remain the same (see Figure 2).

In order to provide methods by which the thermal resistivity can be estimated for specific soils of known properties, investigators have taken two approaches:

- o Theoretical equations based on imaginary models in which the actual soil structure is simplified in such a way as to permit rigorous mathematical analysis of the composite soil-water-air system.

- o Empirical equations based on index properties obtained by field and laboratory measurements.

In general, the soil parameters necessary for theoretical analyses cannot be obtained from standard soil classification tests, and therefore the resulting equations are difficult to use in the absence of special testing. As the empirical equations are based on correlation of index properties with measured thermal performance, they tend to be more reliable than the theoretical equations. This and the fact that the empirical equations use standard measured soil properties, result in these equations being more commonly used to evaluate thermal resistivity. However, as the empirical equations are based on a large number of test results, they tend to give averaged values of thermal resistivity, and some variation between the calculated and actual results should be expected.

No field or laboratory soil testing has been performed during this and previous investigations by ESA and EDAW in the Study Area. Consequently, the level of the input data can justify use of only the least complex of the various empirical equations. For this reason, we have used the "kersten" equations (Figure 1). These equations classify a soil as either a silt-clay soil or a sandy soil and the only other soil parameters required are the dry density and the moisture content. These equations may be represented by a nomogram (Figure 2) where the points C and S are used for clay and sand soils, respectively. An investigation by Makowski and Mochlinski has shown that the theoretical equation developed by Gemant can also be represented on the same nomogram when the line marked " % of clay" corresponds to the "Gemant data", representing the percentage of clay

FIGURE 1

a. Kerstens Equations:

1. <u>Silt and Clay Soils (water content 7% or more)</u>

$$k = \left[1.3 \log (\text{water content}) - 0.29 \right] 10^{0.01\gamma - 3}$$

2. <u>Sandy Soils (water content 1% or more)</u>

$$k = \left[1.01 \log (\text{water content}) + 0.58 \right] 10^{0.01\gamma - 3}$$

where k - the thermal conductivity in $\frac{\text{watts}}{^{\circ}\text{C-cm}}$

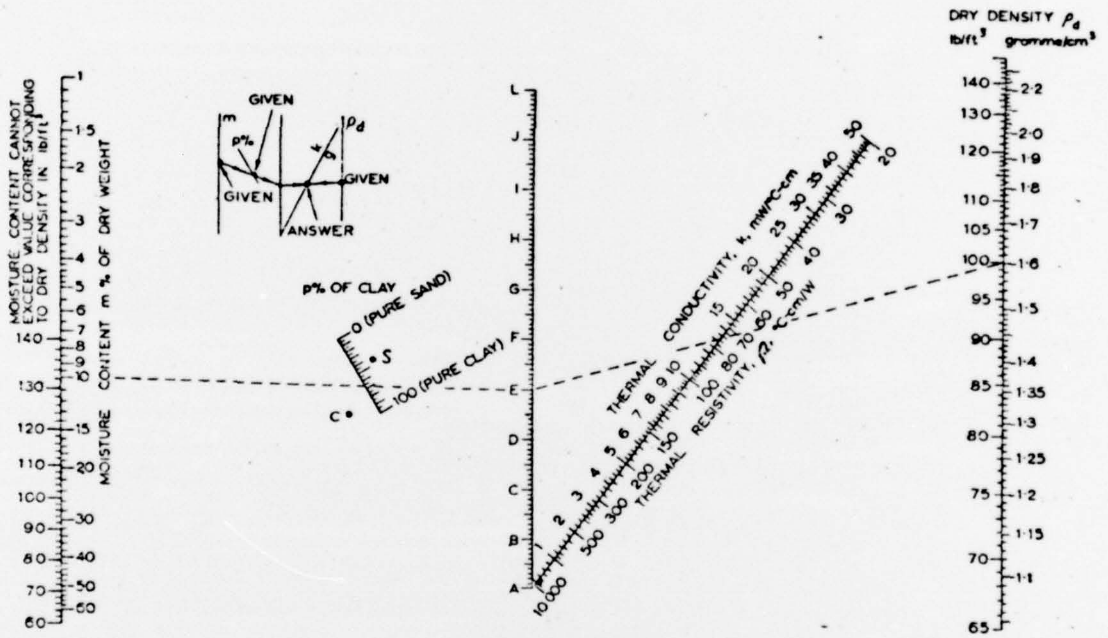
ρ - the thermal resistivity in $\frac{1}{k}$ in $\frac{^{\circ}\text{C-cm}}{\text{watts}}$

γ - Dry Density in pcf.

Note: water content is in % of dry soil weight.

FIGURE 2

b. Nomogram developed by Makowski and Mochlinski.



Nomogram for determination of thermal conductivity and resistivity of sandy soil, given the dry density, moisture content and percentage of clay.

Example: If soil has
65% clay,
10% moisture content,
and 100 lb/ft³ = 1·6 g/cm³ dry density,
k = 13·1 mW/°C-cm; g = 76·5 °C-cm/W.

present in the soil. Investigations have demonstrated that use of this nomogram gives best results when used for relatively dense, moist, sandy soild. Such soils exist in the majority of the Study Area.

Several different methods of evaluating, classifying, and assigning properties to near surface earth materials were considered, including use of surficial geologic data, agricultural soil maps, and others. Based on this comparative review, we concluded that a reasonable source of data was the report "Soil Data, Project Sanguine, Upper Michigan Region Site Study" by EDAW/ESA. Following the same broad soil classifications used in that report, which were based on U. S. Soil Conservation Service reports, we deduced the necessary engineering data based on soil descriptions given. Table 1 summarizes the soil properties that we have assumed, and indicates the probable range of thermal resistivities associated with those properties. The soil units used in Table 1 coincide with the units shown on the EDAW/ESA Soils Map. Because of the wide scatter of test results in developing Kersten's empirical equations and the simplifications assumed in Gemants equations, it is suggested that preliminary design be based on the "Design Thermal Resistivity" (Table 1). It must be emphasized that the classifications used in Table 1 are very broad and that local variations of soil types and properties that affect the thermal resistivity will exist within the classifications. The design thermal resistivities recommended in Table 1 incorporate a factor of safety. They should be used only as a guide for preliminary design and should be field checked at a later stage. It is most probable that field tests will justify the use of somewhat lower values.

Under the classification "Mucky Peat" in Table 1, the values for thermal resistivity given are based on published data for organic soils, as there is no available method of evaluating the thermal resistivity of this type of soil without field testing.

In some parts of the Study Area, bedrock is fairly close to the ground surface. In general, hard, competent rock has a lower thermal resistivity than soil, and for preliminary design, we recommend that a value of

$$80 \frac{^{o}C\text{-}cm}{watt} \text{ be used.}$$

If used as compacted backfill material, all the soils in the Study Area will have similar values of thermal resistivity as they have in their natural state.

TABLE I

Soil Unit	% of Study Area Occupied by Unit	Type of Soil	Assumed Properties: Water Content %	Assumed Properties: Dry Density pcf	Assumed Properties: % Clay	Calculated Thermal Resistivity $\frac{^oC\text{-}cm}{watt}$	Design Thermal Resistivity $\frac{^oC\text{-}cm}{watt}$
Sand	20	Sandy	5-20	105-110	0-5	36-70	120
Sandy Loam	32	Sandy	5-25	100-105	5-10	38-80	120
Silt Loam	38	Sandy	10-30	95-110	10-20	33-71	120
Mucky Peat	8	-	-	-	-	400-700*	700
Alluvium	2	Sandy	5-25	95-100	5-15	42-100	150

(*) Values taken directly from published literature (400 wet, 700 dry).

There are a number of potential problems that we have not attempted to evaluate during the present investigation that can significantly affect the thermal resistivity of a soil. The possibilities of moisture migration and freezing of the soil are potentially the most significant in the Study Area.

The phenomenon of moisture migration is caused by a strong heat source driving the water in the surrounding soil away, thus reducing the soil moisture content and increasing thermal resistivity. At present, this phenomenon is not well understood, and it is difficult to predict with any degree of certainty. Permeable soils are more susceptible to moisture migration; hence, it is most likely to occur above the natural water table in clean sandy soils.

Seasonal soil freezing appears to increase the thermal resistivity by as much as 50 percent. In the Study Area, the depth of frost penetration may be as much as 7 feet, hence, seasonal freezing probably could have a significant temporary effect on heat dissipation if the heat flux is insufficient to prevent frost penetration.