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Ground-water investigations of the Marquette Iron-mining district, Michigan

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ABSTRACT

This report discusses the source, occurrence, and distribution of ground water on the Marquette iron-bearing range of Michigan. The district has produced ore continuously since its discovery in 1844 and at present about 5 million tons is shipped annually, mostly from underground mines. The purpose of this study was to define the principles involved in the movements of surface and ground water toward the mined areas with the hope that the information obtained by the research would lead to development of economical methods of water control, and thus to a reduction in mining coats in this district and, by extension, in other districts. This investigation was begun in 1948 and carried out by the United States Geological Survey in cooperation with the Michigan Geological Survey Division of the Department of Conservation.

The iron ore is mined from rocks of the Huronian series, consisting mainly of slates, graywackes, cherts, dolomites, conglomerates, schists, basic intrusives, and iron-formation. The bedrock crops out in about 10 percent of the area and elsewhere is covered with an overburden of glacial drift ranging in thickness from a few feet to several hundred feet. The ore-bearing rocks occur in a west-trending canoe-shaped, synclinorium extending from the shore of Lake Superior near the city of Marquette, through the Ishpeming-Negaunee area, westward to Lake Michigamme where the synclinorium opens into a broad basin. The rock structure within the synclinorium is extremely complicated by many tight folds and faults, and as well as by numerous diabasic sills and dikes.

Ground water, in some places saturating a thickness of as much as 200 feet of overburden, apparently seeps into the bedrock and follows the more permeable formations to the mine workings. On some properties where mining is done by caving methods the flow is through the broken ground where the mines have been caved directly to the bedrock surface.

The buried bedrock topography underlying the glacial materials was contoured from data on about 3,000 test borings and wells furnished by the mining companies. The bedrock topography is the result of structural features and differential erosion of the bedrock strata. The basic intrusives were most resistant, and the iron-formation was generally the least resistant of all the rocks. The contours show several buried valleys beneath which the iron-formation is known to lie at the bedrock surface and under which mining operations are taking place.

Changes in environmental conditions during the Pleistocene epoch locally caused the following

generalized sequence of depositions basal till; lacustrine sand, silt and clay; outwash sand and gravel; lacustrine clay and marl; and later till. Recent muck, peat, sand and gravel overlie the Pleistocene deposits in some places. No criteria have been developed to indicate, except in a general way, the distribution of permeable and impermeable materials below the land surface.

A map of the water table shows that the ground water everywhere moves toward surface drainage courses except in areas in which heavy pumping has developed cones of depression. The recharge is predominantly from rainfall. As determined by study of fluctuations of the water table, it amounts to about 7 inches per year or about 22 percent of the normal precipitation. Induced recharge from the Carp River at the Morris mine exceeds 400 gpm, but elsewhere in the district leakage from the streams and ditches is of minor magnitude. However, if mining operations cause additional subsidence in the vicinity of these drainage channels, the rate of induced recharge may become larger.

Studies of the rate of pumping from the mines and fluctuations of the water levels in wells in the glacial overburden indicate that in the vicinity of those mines where land subsidence has broken the bedrock surface lowering the water table reduces the rate of inflow into the bedrock. Where the bedrock remains intact no relation is apparent between the amount of water pumped from the mine and the head of the water in the glacial overburden.

Pumping tests in wells of the district indicate an average transmissibility in the glacial overburden of less than 20,000 gpd per foot -- a low value for such material. Such poorly permeable water-yielding materials are not conducive to the development of wells or drainage structures having high yields or large cones of influence. Nevertheless, wells having even small yields near the areas where bedrock is broken would diminish the quantity of water entering the mines. Because of irregularities in deposition of the overburden, especially the discontinuity of the permeable materials, many problems in the control of ground water remain unsolved. Field and laboratory tests of the permeability of the bedrock show it to be generally very low. However, supercapillary fractures and fissures in the iron-formation greatly increase its ability to transmit water. Fracturing caused by subsidence and mining operations increases the permeability further thus permitting larger flows to enter the mine workings.

A number of chemical analyses show (1) that the water in the glacial overburden is a moderately mineralized calcium bicarbonate water, (2) the water entering the mines in considerable quantities is of similar character, but (3) that from the drips and seeps at lower levels is more highly mineralized, with sodium, sulfate, and chloride predominating.

INTRODUCTION

A study of water and its relationship to mining operations in the iron ranges of Michigan was begun in July 1945 by the United States Geological Survey in cooperation with the Geological Survey Division of the Michigan Department of Conservation. The report on the first work, Technical Report No. 2 of the Michigan Geological Survey Division -- Ground-water problems of the Iron River district, Michigan, by W. T. Stuart, C. V. Theis, and G. M. Stanley. summarized the investigation on the western part of the Menominee iron range in 1948. The second project on the Marquette iron range, is the subject of this report. The studies are made under the general direction of A. N. Sayre, Chief, Ground Water Branch, U. S. Geological Survey, and under the direct supervision of the senior author.

Purpose and Scope of This Investigation

The area of investigation, known as the Marquette iron range, is in the north-central part of the northern peninsula of Michigan in the central part of Marquette County (see fig. 1). The district, as used in this report, includes the eastern part of the range or iron-bearing synclinorium in the vicinity of the cities of Negaunee and Ishpeming and westward to the center of T. 47 N., R. 29 W. and embraces an area 15 miles, long and 8 miles wide (see fig. 2). The synclinorium extends about 15 miles westward beyond the limits of the area covered by this report, but most of the mining is done within the report area. Fourteen operating mines -- 11 underground mines and 3 open pits ship more than 5 million tons of ore yearly.

Previous Investigations

Since the discovery of iron ore in 1844 many Federal, State, and private studies of the bedrock geology have been made, but no investigation of ground water was attempted other than the analysis of samples of water from the mines by Lane in 1911. In 1897, U. S. Geological Survey Monograph 28 with an atlas of 39 plates first summarized the geology of the range. In 1911, Monograph 52 again summarized the known bedrock geology. In 1917, Frank Leverett studied the glacial geology of a very broad area in the Lake Superior region but did little detailed work on the Marquette range. In 1930, C. O. Swanson of the Michigan Geological Survey investigated the bedrock geology of a portion of the range from North Lake west to Humboldt, and in 1931. Justin Zinn also of the Michigan Geological Survey investigated the section between Humboldt and Lake Michigamme. The results of many individual studies are included in technical journals such as those of the Society of Economic Geologists, the American Institute of Mining and Metallurgical Engineers and the Lake Superior Mining Institute.

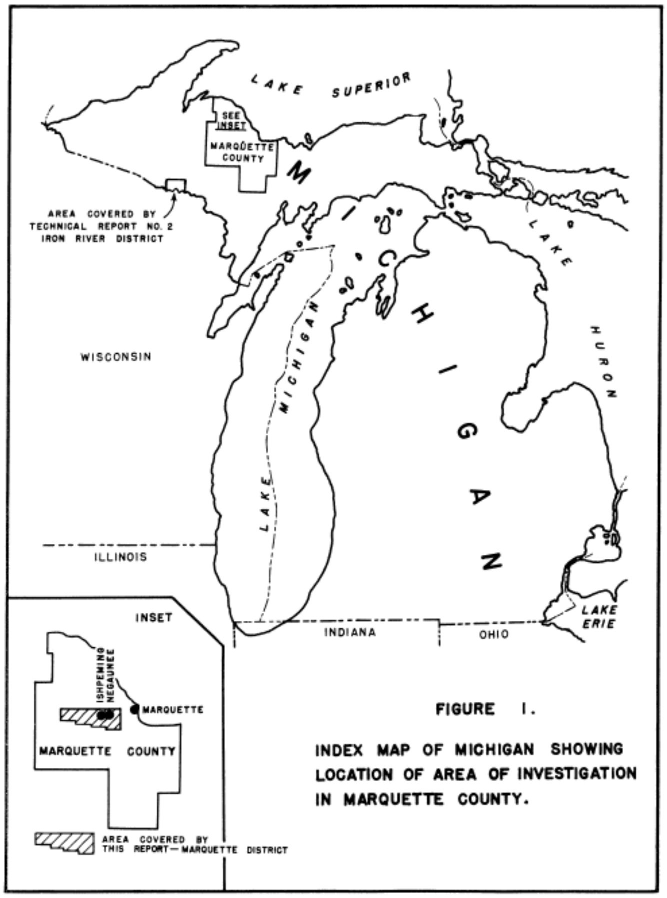

Figure 1. Index map of Michigan showing location of area of investigation in Marquette County.

Present Investigation

This report on the hydrology of the district deals essentially with ground water above the "buried "bedrock surface and covers in detail that part of the area lying between the granite complexes that bound the synclinorium on the north and south. Water outside the synclinorium does not affect mining operations.

Methods of Investigation

The ground-water investigation of the Marquette iron-mining district has included collecting and interpreting all of the available data bearing on the occurrence, source, movement, disposal, and quantity of water involved. The buried bedrock topography has been mapped (see fig. 3) to give information concerning the areal extent, depth, shape, and degree of interconnection of the ground-water reservoirs which occupy the low points in the bedrock basins. The surficial geology has been mapped (see fig. 4) to indicate those areas where porous materials capable of accepting water are found at the land surface. The ground-water surface has been mapped (see fig. 5) to indicate the general direction of ground-water flow. Recharge representing the addition of water to the ground-water reservoirs was evaluated both from the rises in the ground-water levels in wells and from percolation-loss investigations in several surface streams of the district. The character of the materials in which ground water is stored in the buried bedrock basins was determined from the study of drill cuttings, logs of exploration holes, and from observations of the surficial materials. The hydraulic characteristics of the materials filling the ground-water reservoirs were determined by means of pumping tests and by observations of the behavior of the water levels in the vicinity of drainage structures.

The maps in this report are a composite of all information available. The base was taken mainly from control maps furnished by the Cleveland-Cliffs Iron Co. Many corrections in the locations of the highways, railroads, streams, and lakes were made by comparison of the base with the 1939 Agricultural Adjustment Administration aerial photographs. The altitudes used are based on the vertical control of the U. S. Geological Survey and the U. S. Coast and Geodetic Survey and are the same as those used by the mining companies. In the areas remote from active mining operations, altitudes of the land surface for drill holes and farm wells were obtained from the atlas accompanying U. S. Geological Survey Monograph 28 (Van Hise, 1897).

In the winter of 1948, pumping tests in the wells of the Morris mine and at the Mather A shaft were made by W. T. Stuart. Depth-to-water measurements in selected observation wells to determine the fluctuations of the water table were begun in the spring of 1948 in areas unaffected by mining operations. This supplemented the observations made by the mining companies in wells on their present properties. Water levels in 62 observation wells were measured monthly or oftener and continuous water-level fluctuations in 6 observation wells were obtained with recording gages. After July 1948, E. C. Rhodehamel and E. A. Brown began mapping the surface geology, locating outcrops, and inventorying the farm wells and springs. During the periods of reduced field work about 3.000 records of exploratory drilling, logs of overburden materials, and altitudes of bedrock exposures were obtained and plotted for the construction of a map of bedrock topography. Samples of drill cuttings, collected during the summer drilling program, were logged by H. C. Boback. The Surface Water Branch of the Federal Survey computed the records of streamflow and assisted in making many of these measurements.

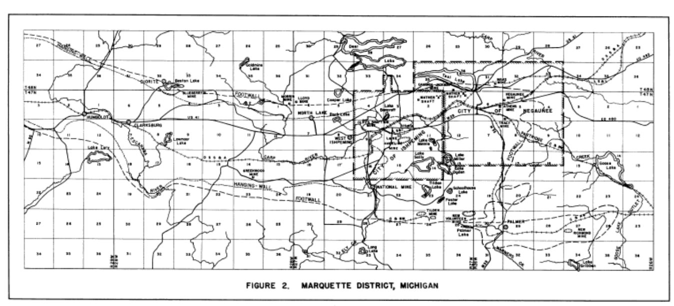

Figure 2. Marquette District, Michigan.

Acknowledgments

The study was made possible through the wholehearted cooperation of the mining companies, who contributed maps and records of the diamond drill explorations, water-level observations, and pumpage. The mine operators in the district are the Cleveland-Cliffs Iron Co. (Athens, Cambria-Jackson, Cliffs Shaft, Lake, Lloyd, Maas, Mather, and Tilden mines); Inland Steel Co. (Greenwood and Morris mines); North Range Mining Co. (Blueberry mine); M. A. Hanna Co. (Richmond mine); and Pickands Mather & Co. (New Volunteer mine). Nonoperating companies who contributed many records are the Jones & Laughlin Ore Co., Oliver Iron Mining Co., and Ford Motor Co. F. G. Pardee also provided information on drill explorations. The writers are indebted to the members of the geologic and engineering staffs of the companies of the district for many personal observations and discussions which added considerable information.

GEOGRAPHY

Culture

The two incorporated cities within the district, Ishpeming and Negaunee, have populations of approximately 11,000 and 8,000 respectively. Both cities can be reached from the south by the Chicago & North Western Railway Co. and from the west and east by The Duluth, South Shore & Atlantic Railroad Co. The Lake Superior & Ishpeming Railroad hauls freight, chiefly ore from the mines to the docks in Marquette. U. S. Highway 41 traverses the northern part of the district in an east-west direction. Mining is now the most important industry; lumbering and the manufacturing of wood products, formerly important, are greatly reduced from the scope of former years.

Topography and Drainage

The Marquette district is in an outcrop area of pre-Cambrian rocks. The relatively strong resistance of these rocks to the forces of degradation and weathering have resulted in an area of high bedrock altitudes, resembling a plateau with locally rough topography, The highest point in the area, about 1,870 feet above sea levels is the top of Summit Mountain, 3 miles south of Negaunee. The lowest points are southeast of Goose Lake and south of the village of Palmer, where the land surface is below 1,200 feet in altitude. In the central and western parts of the district there are no large hills or deep valleys and the relief is more moderate. However, as a unit, the district is a topographic highland and a headwater drainage area. The Carp River system drains the north and east sides of the district, and small streams which unite south of the district to form the Escanaba River drain the south and west sides.

The topography is locally modified by numerous pits or subsidence areas in the vicinity of old abandoned mines and near some of the active mines. These pits are the result of a sloughing of the surface materials in filling the voids formed when the iron ore was removed through mining. These pits are numerous in the vicinity of Ishpeming and Negaunee and many are often filled with water, but they occupy a very small percentage of the total area. The largest of these is the present Lake Angeline basin which occupies about 200 acres.

Climate

The climate of the district is not as extreme as that in other States of similar latitude, because Lake Superior moderates the extremes of heat and cold. According to the published records of the U. S. Weather Bureau, the mean annual air temperature at Marquette, on Lake Superior, is 41°F.; Whereas 15 miles west, at Ishpeming, where the altitude is 800 feet above that of Marquette, the mean annual temperature is 39.8 F. At Ishpeming the annual range of temperature is from the lower 90's above zero to the upper 30's below zero.

The annual precipitation for the years 1930 to 1952 for both Ishpeming and Marquette are shown in table 1. The normal yearly precipitation at Marquette is 32.54 inches and at Ishpeming, 31.00 inches. Table 2 shows the normal monthly precipitation and mean temperature for both Ishpeming and Marquette, February is normally the driest month and July, the wettest. The annual snowfall at Marquette has ranged from about 76.3 inches to 188.0 inches in the last 5 years. The eastern part of the district, although close to Lake Superior, has a greater snowfall owing to the fact that the air charged with moisture from the lake becomes chilled as it rises and precipitates snow, not only throughout the winter months, but often from early October to the beginning of May, so that the ground is frequently covered half the year.

Year	Ishpeming,	Marquette,
1930	23.14	26.85
1931	36.70	32.59
1932	31.20	27.93
1933	28.72	29.01
1334	32.87	31.42
1935	27.19	28.27
1936	30.18	30.40
1937	30.13	31.27
1938	35.32	34.85
1939	33.57	35.91
1940	30.34	30.98
1941	32.20	32.46
1942	34.34	35.11
1943	32.04	32.90
1944	32.77	33.90
1945	--	32.27

1946	26.37	25.97
1947	32.83	32.82
1948	22.02	22.46
1949	37.23	38.72
1950	30.64	33.41
1951	43.50	41.59
1952	24.35	25.23
Normal	31.00	32.54

Table 1. Annual precipitation, in inches, for the years 1930-1952.

	Ishpeming, Mich.		Marquette, Mich.	
Month	Precipitation (inches)	Temperature (°F)	Precipitation (inches)	Temperature (°F)
January	1.53	13.4	2.33	16.3
February	1.44	13.7	1.97	16.3
March	1.87	23.6	2.26	24.8
April	2.32	37.9	2.43	37.8
May	2.93	50.4	2.96	49.0
June	3.41	45.8	3.22	58.9
July	3.85	65.5	3.12	64.9
August	3.15	63.4	2.67	63.8
September	3.67	55.9	3.25	57.5
October	2.75	45.1	2.76	46.2
November	2.56	30.5	2.91	33.3
December	1.52	18.4	2.66	22.6
	Total 31.00	Mean 39.9	Total 32.54	Mean 41.0

Table 2. Monthly normal precipitation and mean temperature.

GEOLOGY

Introduction

A knowledge of the geology of the area is necessary to provide a framework on which an understanding of the occurrence and movement of ground water can be based. The framework is the delineation of the areal extent, depth, shape, and degree of interconnection of ground-water reservoirs, obtained from the interpretation of the existing features and written records. Knowledge of the filling of the bedrock basins by glacial action strengthens the understanding of the general conditions and offers an explanation for the unusual occurrences and movements of ground water in specific areas.

In the Marquette district the general strong resistance of the pre-Cambrian rocks to degradation and weathering has resulted in an area of high bedrock altitude; however, local relatively nonresistant formations within the synclinal structure have been partially eroded, forming depressions which filled with glacial sediments, now constitute the ground-water reservoirs.

Fenneman (1938, p. 537) states that the district is a southward extension of the old Laurentian Upland which he described as being a perfect to a very imperfect peneplain. The post-Keweenawan history and physiographic development of the Lake Superior region are summarized by Van Hise and Leith (1911, p. 558) in the following list of events:

1. “the great pre-Cambrian mountain making and erosion,
2. subsidence and Paleozoic sedimentation,
3. the post-Paleozoic uplift and denudation,
4. the deposition of Cretaceous rocks upon parts of the region,
5. the post-Cretaceous uplift and succeeding denudation, and
6. the Pleistocene ice incursions.”

Consolidated Rocks

Stratigraphy

The geologic section of formations in the Marquette district, including the Pleistocene (glacial) and Recent deposits, are listed in table 3 with their sequence, lithology, and thicknesses.

The consolidated rocks are of both sedimentary and igneous origin. All the sedimentary rocks and many of the igneous rocks have undergone intense metamorphism and folding. The geology of these rocks in the Marquette district as reported by Leith, Lund, and Leith (1935, pp. 1-10) is summarized below.

The oldest rocks are schists of the Keewatin series. The next oldest are the Laurentian series, composed of intrusions of granite, syenite, peridotite, and gneiss. An unconformity exists between this complex and the overlying Huronian series.

The Huronian series, whose total thickness in the Marquette district probably exceeds 109000 feet, is divided into three parts: (1) the lower Huronian, composed of quartzite, dolomite. and slate; (2) the middle Huronian, composed of quartzite, slate, and the Negaunee iron-formation which is the principal source of iron ore; and (3) the upper Huronian, composed of quartzite, iron-formation, volcanic rocks, and slates with an included iron-formation member. Unconformities exist at the base of the middle and upper Huronian which provides a natural division of the series.

Following the deposition of the upper Huronian, basic intrusives consisting partly of sills and laccoliths were intruded into these rocks. The rocks subsequently were strongly deformed and locally intruded by Killarney granite. An unconformity exists at the surface of the Killarney granite. Within the area of the report unconsolidated glacial and postglacial deposits overlie unconformably the older consolidated rocks in most places.

Structure

The Huronian rocks lie in a great synclinorium between the northern and southern areas of pre-Cambrian rocks. The synclinorium is canoe-shaped and from about 6 miles west of Lake Superior trends roughly west for about 33 miles, approximately to the center of Lake Michigamme, where it opens into a broad basin. (See U. S. Geol. Survey Mon. 52, Pl. 17.) The greatest width of the synclinorium, about 6 miles, is north-south along the center line of R. 26 W., 2 miles east of the city of Negaunee; the narrowest width, about 2 miles, is half a mile east of Lake Michigamme. A large structural basin roughly 16 square miles in area, referred to as the Negaunee Basin, is in the east-central part of the synclinorium, and is confined generally to the area between the cities of Ishpeming and Negaunee on the north and the villages of National Mine and Palmer on the south. The Negaunee iron-formation in this area has been extensively intruded by post-Huronian basic rocks.

System	Series		Formation or unit	Rock type	Thickness (feet)
Quaternary	Recent		Alluvium, swamp, and lacustrine deposits	Silt, clay, sand, gravel, muck, marl, and peat deposited in rivers, swamps, and lakes	10
Quaternary	Pleistocene		Glacial drift: Till Outwash Lacustrine deposits	Unstratified to slightly stratified heterogeneous mixture of sand, gravel, clay, and boulders Sand, gravel, cobbles, and boulders Fine sand, silt, and clay	0 to 283
			Unconformity		
Pre-Cambrian	Killarney granite*		Acidic intrusives	Granite	---
Pre-Cambrian	Keweenawan		Basic intrusives	Diabase and basalt ("diorite")	---
			Unconformity		
Pre-Cambrian	Huronian	Upper	Michigamme slate (including Bijiki iron-formation member)	Slate and mica schist (grunerite-magnetite schist and sideritic chert)	1,000 to 2,000
Pre-Cambrian	Huronian	Upper	Clarksburg volcanics	Greenstone and conglomerate (cut by diabase and basalt)	Several thousand
Pre-Cambrian	Huronian	Upper	Greenwood iron-formation	Grunerite schist with chloritic material and quartz sand; sideritic slate containing specular hematite or masses of "specularitic schist"	About 50
Pre-Cambrian	Huronian	Upper	Goodrich quartzite	Quartzite and conglomerate	1,550
			Unconformity		
Pre-Cambrian	Huronian	Middle	Negaunee iron-formation	Sideritic slate, grunerite-magnetite schist, ferruginous slate and chert, and jaspilite	About 1,500
Pre-Cambrian	Huronian	Middle	Siamo slate	Slate, graywacke, and "quartzite"	About 650
Pre-Cambrian	Huronian	Middle	Ajibik quartzite	Quartzite (with slate, graywacke, and basal conglomerate)	700 to 900
			Unconformity		
Pre-Cambrian	Huronian	Lower	Wewe slate	Slate (with graywacke, conglomerate, and mica slate and schist)	1,050
Pre-Cambrian	Huronian	Lower	Kona dolomite	Cherty dolomite (with slate, graywacke, and quartzite)	700 to possibly 1,400
Pre-Cambrian	Huronian	Lower	Mesnard quartzite	Quartzite (with conglomerate, graywacke, and slate)	670
			Unconformity		
Pre-Cambrian	Laurentian		Granite, syenite, and peridotite	Granite, syenite, and peridotite	---
Pre-Cambrian	Laurentian		Palmer gneiss	Gneiss	---
Pre-Cambrian	Keewatin		Kitchi schist	Basic schist	---
Pre-Cambrian	Keewatin		Mona schist	Basic and acidic schist	---

*Stratigraphic position doubtful

Sources of data: U. S. Geol. Survey Mon. 28
U. S. Geol. Survey Mon. 52
U. S. Geol. Survey Prof. Paper 184
Michigan Geol. Survey Centennial Geological Map of the northern peninsula of Michigan

Table 3. Geologic formations of the Marquette district.

Faults, many of which are several miles in length and have throws of more than 1,000 feet, are very common in the area. The largest is the Palmer fault, which lies about half a mile north of the village of Palmer. This normal fault trends roughly east-west for about 6 miles through the S½, T. 47 N., R. 26 W. and extends into the SE¼, T. 47 N., R. 27 W. Apparently the magnitude of the throw is several thousand feet and the horizontal movement displaces a portion of the southern limb of the synclinorium eastward several miles. Another fault nearby is the Volunteer fault, which trends about N. 60° E. from the Old Volunteer mine in sec. 31, T. 47 N., R. 26 W. and is a high-angle oblique normal fault having a horizontal displacement of 2,000 feet or more. Many minor faults have been mapped in the district along the south half of the synclinorium from National Mine to Humboldt and along the north half of the synclinorium in the vicinity of Teal lake. Many other faults exist in the western part of the district along the northern limb. Some have been reported in publications, but others, some of even greater magnitude, have not been mapped. Mining operations in the Ishpeming-Negaunee area have revealed many faults, some of which are of considerable length and with large displacements. The writers have observed that faulting has caused the many abrupt changes of strike of the competent formations along the limbs of the synclinorium that were formerly explained by folding.

Bedrock Topography

The district has undergone extremely long and complex physiographic development which probably occurred in the following manner: (1) In Proterozoic time an imperfect peneplain surface was developed through several cycles of denudation, and this peneplain surface was subsequently dissected in an erosional cycle which was interrupted in a youthful stage; (2) in the Pleistocene epoch the resulting erosion surface was then acted upon by the forces of glaciation; and (3) the Recent stage of development is due to the erosion of the bedrock by present-day streams, which are not everywhere eroding the bedrock surface because they have been unable to completely remove the deposits laid down during the Pleistocene.

Figure 3 is a topographic map of the bedrock surface or "ledge" most of which is buried by glacial drift. (In the Lake Superior region the term "ledge" is used to designate bedrock regardless of the lithology and whether buried or exposed; but locally, the term is sometimes applied only to the buried bedrock surface.) The contours of the bedrock topography are based on several forms of data: (1) field mapping of locations and altitudes of outcrops; (2) office plotting of the bedrock surface as determined from all available drill-hole records and seismic data; (3) study of the continuity of bedrock exposures; (4) study of the comparative erosional resistance of the various formations; and (5) study of the present physiography, especially the existence of large valleys that contain small streams which are not compatible to the amount of erosion and the time needed to form these valleys. The information on the altitude of the bedrock surface is highly concentrated near explored ore bodies and is generally scattered elsewhere. Unfortunately, the areas of abundant information form a small percentage of the entire area.

A contour interval of either 20 or 100 feet was used in construction of figure 3 depending on the concentration of data. Solid contours are used in areas where the information on the altitude of the bedrock surface is both accurate and plentiful. Dashed contours indicate a lesser degree of accuracy. Question marks indicate doubtful interpretation of topographic features.

Relief

The bedrock relief shown on figure 3 is not uniformly rough or moderate, each condition may be found near the other. The highest rock altitude is 1,870 feet in the S½SW¼ sec. 24, T. 47 N., R. 27 W. at the top of Summit Mountain. The lowest recorded altitude of the bedrock surface, 1,087 feet, is in a drill hole in the SW¼ sec. 26, T. 47 N., R. 26 W. The known relief of the bedrock surface in the area of the report is 783 feet, which is 136 feet greater than the land surface relief of 647 feet. The bedrock valleys, however, are much deeper than the 136-foot difference implies. Several bedrock valley floors are more than 200 feet below land. surface arid one bedrock valley in sec. 22, T. 47 N., R. 28 W. has a depth of approximately 285 feet below land surface.

Areas in which the bedrock is high, whether exposed or covered by a thin layer of glacial drift, and which have a rough topographic surface in a youthful stage of erosion, are present (1) along the north and south limbs or borders of the synclinorium, although at some places the bedrock surface along the southern border of the synclinorium is subdued, (2) within the synclinorium in the Negaunee “structural" Basin, and (3) in the areas immediately south and east of Goose Lake, These areas are indicated on the ledge map as the large areas of numerous rock outcrops. The tops of most of these highland masses range from 1,600 to 1,800 feet in altitude, and represent the present top of the old peneplain surface. The lowlands between these elevated tracts are generally underlain by less resistant rocks. The latter areas are generally well-covered with glacial drift. The present topographic forms on the high bedrock masses were used as a guide in mapping the buried bedrock surface.

Comparative erosion resistance of the bedrock strata

A study of the comparative resistance of the bedrock formations was made primarily to extend the known data concerning the altitudes of the bedrock surface. In comparing the resistance of rocks in the Marquette district to the younger sedimentary strata to the east and southeast, all the rocks within the district would be classified as being highly resistant; otherwise, these rocks, long exposed to processes of erosion and weathering, would not stand at their present altitudes. Nevertheless, within the district certain formations show a pronounced ability to withstand erosion and weathering while other formations appear to have less resistance. Certain ones, the Siamo slate, the Ajibik quartzite, and the Killarney granite are resistant in one area yet do not demonstrate strong resistance in other areas (see table 3). This may be due to a change in lithology within the formations, but probably much of the apparent change in the relative erosion resistance of a formation from one area to another is due to a change in the association of surrounding strata and to changes in the thickness of the formation. In general, the older the formation the greater the resistance to erosion. Also it is generally true that the massive rocks are more resistant to erosion whereas the slates or thin-bedded formations show the least resistance to erosion. In local areas exceptions are found to these general tendencies. An example of a massive rock which demonstrates relatively little resistance to erosion is the Ajibik quartzite along the south limb of the synclinorium in the west and central parts of the area. This condition may have resulted from much fracturing of the formation. Table 4 lists the observed comparative resistances of bedrock strata with the most resistant formations having the lowest numerical number. Table 5 is a key to the relative resistance for each formation identified in the eastern, central, and western parts of the district.

Development of the bedrock erosion pattern

The bedrock erosional pattern was established as a result of bedrock-strata resistance and structural controls. The larger bedrock valleys trend along the course of relatively weak parallel rock layers. Valleys also developed along zones of weakness such as outcropping igneous-rock contacts, upturned unconformities, bedding planes, and faults. The larger valleys in the area are controlled mainly by the above weaknesses, but occasionally a strong local bedrock structure has been effective in controlling the trend of a large valley. The courses of smaller tributary valleys show a relationship to both rock structure and rock resistance. Faulting, and shear zones developed by the intrusion of the diabasic rocks, are important factors controlling drainage lines in areas where few or no other pronounced rock structures exist.

The bedrock erosional pattern in the Negaunee “structural” Basin, a highland mass, differs from that in the synclinorium west of the Negaunee Basin owing to the presence and orientation of the basic intrusions which have disarranged the synclinal structure. Because of the complex geology of the basin there is no definite type of bedrock erosional pattern. However, a rectangular drainage system associated with the folded strata is probably the most characteristic pattern discernable.

A number of lines of pre-Pleistocene drainage have been located by the contouring of the bedrock surface in fig. 3. They are: (1) eastward from the S½ of secs, 31 and 32, T. 48 N., R. 26 W. to the present Carp River basin; (2) southeastward from sec. 8 through the Goose Lake area in sec. 14, T. 47 N., R. 26 W.; (3) southward from the village of National Mine in sec. 21, through the NE¼ sec. 28, T. 47 N., R. 27 W.; (4) a southward-trending drainage through sec. 22, T. 47 N., R. 28 W.; and (5) a southwestward-trending drainage leaving the report area near the center of sec. 3, T. 47 N., R. 29 W.

Local bedrock valleys

The topography of the bedrock in the vicinity of a mine determines the size and shape of the local ground-water reservoir and hence the amount of water to be pumped at the mine. Mines in areas where the bedrock drainage is limited and where the iron-formation lies high on the topographic slope do not have a high rate of pumping. On the other hand. since the iron-formation is not resistant to erosion and is commonly found under depressions in the bedrock surface, mines located under large bedrock valleys, particularly under the lowest parts of the buried valleys, pump larger amounts of water.

Everywhere resistant	Locally resistant	Little resistance everywhere
1. Basic intrusives into upper Huronian	1. Granite extending along southern boundary of district	1. Michigamme slate
2. Kitchi and Mona schists	2. Ajibik quartzite	2. Wewe slate
3. Granite north of Boston Lake	3. Goodrich quartzite	3. Negaunee iron-formation
4. Mesnard quartzite	4. Siamo slate	4. Clarksburg volcanics
5. Kona dolomite	5. Bijiki iron-formation member	5. Greenwood iron-formation.

No. 1 is most resistant

No. 5 is least resistant.

Table 4. Scale of comparative erosional resistance of bedrock formations.

The following discussion of local bedrock valleys indicates the role that the known geologic structure had in the erosional development of the area, and it is believed that as further information on the structure is obtained the knowledge of the bedrock topography can be extended.

NORTH LAKE AREA -- secs. 1, 2, 3, and 4, T. 47 N., R. 28 W.

The major topographic feature of this area is a large northwestward-trending ridge of resistant rock. On both sides of this ridge, strike valleys have been developed upon comparatively easily eroded, thin-bedded, formations. The bedrock surface of the valley north of the ridge has been defined in detail by extensive drilling, but south of the ridge the information is sparse. In the S½ sec. 1, where much detail is known, the unevenness of the bedrock surface is a feature of the area. The dissection and sharp contrasts in the topography of the area strongly suggest erosion along fracture and fault zones. Many transverse faults and intrusions have been mapped (Swanson, 1929) parallel to southwest-trending transverse valleys in the vicinity of the Blueberry mine in sec. 3, T. 47 N., R. 28 W. and in N½ sec. 2.

Formation	Eastern area	Negaunee Basin	Western area
Killarney granite	R-H	NSR-LHlv	NSR-LHlv
Basic intrusives	R-H	R-H	X
Michigamme slate:			
Upper part	X	X	NR-V
Bijiki iron-formation member	X	X	NSR-LHlv
Lower part	X	NR-LVlh	NR-LVlh
Clarksburg volcanics	X	NR-V	NSR-LVlh
Greenwood iron-formation	X	NR-V	NR-V
Goodrich quartzite	NSR-LHlv	NSR-LHlv	NSR-LHlv
Negaunee iron-formation	NR-LVlh	NR-LVlh	NR-V (north limb) NSR-H (south limb)
Siamo slate	NR-V	NSR-LHlv	NR-V
Ajibik quartzite	R-H	NSR-LHlv	NSR-LVlh
Wewe slate	NR-LVlh	X	X
Kona dolomite	R-H	X	X
Mesnard quartzite	R-H	X	X
Granite of the Laurentian series	R-H	X	X
Kitchi and Mona schists	R-H	R-H	X

Key: X - not found or identified
R - resistant
NSR - not strongly resistant
NR - not resistant
V - Large valleys
H - Large hills or ridges
LHlv - Large hills and local valleys
LVlh - Large valleys and local hills

Table 5. Bedrock formation erosional resistance by area.

The northeast-southwest-trending breaches or gaps in the main buried ridge are all located at the site of structural discontinuities except in the S½ sec. 1, where faulting east of the area has seemingly permitted the bedrock structure to be eroded unevenly. The total drainage area of this bedrock valley is roughly 2 square miles, and the average gradient is approximately 10 feet per mile in a southeasterly direction. The bedrock floor of the valley is approximately 200 feet below land surface.

CARP RIVER AREA WEST AND NORTH OF ISHPEMING -- secs. 7, 8, 17, and 18, T. 47 N., R. 27 W., secs. 11, 12, 13, 14, and 15, T. 47 N., R. 28 W.

No prominent ridges either exposed or buried are found in this area, but several valley structures are indicated by scattered drilling. South and east of the Morris mine area in sec. 1, are two east-west valley structures, the northern one lying in the N½ secs. 7 and 8 and the southern one lying along the Carp River in the N½ secs. 17 and 18, T. 47 N., R. 28 W. Probably these valleys connect at the west end with a postulated channel, although no data support this theory. This postulated channel would head in the NW¼ sec. 12, T. 47 N., R. 28 W., as a continuation of the Morris mine transverse valley and trend southwestward through secs. 11, 14, and 15, leaving the area of investigation in E½, sec. 22, T. 47 N., R. 28 W. in a known low-altitude gap in the south limb of the synclinorium. More information is available on the eastern end of these two east-west valley structures where they join in a valley with a northeastward gradient which underlies the present Carp River.

Joining the southern valley in W½ sec. 17, T. 47 N., R. 27 W. are two tributaries which head in the highland areas of the Negaunee "structural" Basin. The southernmost of these valleys heads in the NW¼ sec. 21, T. 47 N., R. 27 W. and joins the main drainage near the center of sec. 17. The northern tributary has two major forks, one with a westward gradient along the south line of sec. 10, and the other a sinuous channel which heads at Lake Sally and trends just south of and against a very wide prominent basic intrusive rock ridge. This valley joins the other in the NE¼ sec. 16. Along these tributaries, are amphitheatres at different altitudes, indicating local base-level controls owing to the very resistant bands (dikes and sills) of basic intrusive rocks intruded into the less resistant Negaunee iron-formation.

North of the high east-west bedrock ridge, in the center sec. 10, T. 47 N., R. 27 W. is a prominent westward-sloping partly buried bedrock valley joining the major drainage in the N½ sec. 9. This valley was incised into a series of strata of the Negaunee iron-formation between more resistant quartzite to the north and intrusives to the south. In the S½ sec. 3 the bedrock surface is not well-defined, and narrow drainage passages are possible along folds in the less resistant Negaunee iron-formation or along faults to the north or west. However, the development of gradients along the bedrock valley flanks, according to drill-hole information, indicates lowest gradients to be south and thence west.

In the main northeastward-trending valley of the Carp River basin, (sec. 4, T. 47 N., R. 27 W.) west of Lake Bancroft, the drilling records do not indicate the existence of a bedrock channel gradient from the area west of Ishpeming to the north. In fact, the data indicate the altitude of the bedrock surface rises in the northern part of the valley. Should this channel be continuous there are two locations through which it may pass: (1) under the present Carp River channel; (2) northeastward under Lake Bancroft. Either valley would be cut through basic intrusive masses, and would necessarily follow areas of weakness such as faults or shear zones. The westernmost and most probable site of the valley would cut through the thinnest band of basic intrusives. From the known geologic structure and the bedrock altitude evidence it appears that the lowest gradient is in the western channel in the NW¼SE¼ sec. 4. The valley floor is probably about 140 feet below the land surface.

North of the south line of T. 48 N., is a long narrow channel with a steep slope on the north side. The western part heads near Cooper Lake, in sec. 5. T. 47 N., R. 27 W. with a northward-draining tributary heading near Rock Lake. The eastern part is occupied by both the Teal Lake trough and its eastern extension in the vicinity of the Maas and Negaunee mines. West of Teal Lake very little drill-hole information on the depth to bedrock is available. This channel is probably a fault valley eroded into the Siamo slate, although the scarp along the north side has never been mentioned as a fault in published literature. The northeastward-trending bedrock valley of the Carp River enters the Teal Lake trough near the NE cor. sec. 4, T. 47 N., R. 27 W.

MATHER MINES A AND B SHAFTS AREA -- secs. 1 and 2, T. 47 N., R. 27 W.

South of Mather A and B shafts is an east-west channel extending from the Carp River basin in sec. 3 through the N½ secs. 1 and 2, T. 47 N., R. 27 W. It joins the major eastward extension of the Teal Lake trough near the N¼ cor. sec. 6, T. 47 N., R. 26 W. through a short northeastward-trending transverse valley. From a low divide in the center of n½ sec. 2, the gradient of the bottom of this channel is westerly to the Carp River, and easterly from the divide the gradient is toward the Teal Lake trough. The channel has been developed in the Negaunee iron-formation with resistant basic intrusives forming the north and south walls in sec. 2. In sec. 1 the south wall is formed by a resistant facies of iron-formation. The north wall is continuous, but a tributary valley has been eroded across a fold in the Negaunee iron-formation lying between the two resistant strata which form the south wall. The mouth of the tributary is in the NW¼ sec. 1, and the head is near the NE cor. sec. 13. The upper reach of this valley has a very straight northwest course through an alternating wide and narrow trough developed on the Negaunee iron-formation between two steep-sided ridges of basic rocks. Amphitheatres at progressively higher altitudes along its course indicate a local base-level erosion control identical with that in the Lake Sally region (sec. 14, T. 47 N., R. 27 W.). The transverse section of the Mather-mine channel is in general a broad V-shaped valley with the floor about 100 feet below the land surface.

ATHENS MINE AREA -- S½ sec. 6, T. 47 N., R. 26 W.

Joining the Mather-mine channel in the W½ sec. 6, T. 47 N., R. 26 W., is a northwestward-trending valley which heads in the vicinity of the Athens mine area where there are two forks. The south fork extends into the NE¼ sec. 7, and the north fork extends into the NE¼SE¼ sec. 6. The bedrock surface in the SE¼SE¼ sec. 6 is a small relatively flat low surface from which drainage lines radiate east, north, and west. This valley follows the trends of some of the local structures, but appears to be governed more closely by variations of the bedrock erosion resistance. The rather complete dissection of the bedrock surface over this relatively wide area seems to be related to the large amount of intrusion and faulting occurred here.

MAAS AND NEGAUNEE MINES AREA -- S½ secs. 31, 32, 33, T. 48 N., R. 26 W., and N½ secs. 5, 6, T. 47 N., R. 26 W.

The eastward extension of the Teal Lake trough is a buried valley incised into the Negaunee iron-formation along the north limb of the synclinorium in the vicinity of the NW cor. sec. 5, T. 47 N., R. 26 W. The tributary channels from the Mather A and B shafts area and the Athens mine area join this valley, in which the lowest eastward drainage bedrock altitudes were encountered. Drilling in this valley has shown the slopes are much steeper on the north side where the channel abuts against more resistant rocks.

TRACY MINE AREA

This drainage system includes parts of secs. 4, 5, 6, 7, 8, and 9, T. 47 N., R. 26 W. The bedrock basin is connected through a low saddle with the northwestward-trending valley discussed under the Athens mine area. Insufficient drilling has been done to locate a definite outlet for the drainage system. Southeast of a large continuous southeastward-trending ridge of basic intrusive bedrock, in the center of the NW¼ sec. 8, is a southwestward-trending ravine connecting two basinal areas. In the NE¼ sec. 8, and the S½ sec. 5, are some areas of low bedrock altitudes which might either drain northward, joining the eastward extension of the Teal Lake trough east of the Maas and Negaunee mines, or southward through the narrow ravine in the NW¼ sec. 8, to the valley now occupied by the present drainageway of Partridge Creek.

LOWER CARP RIVER AREA -- secs. 33, 34, 35, and 36, T. 48 N., R. 26 W.

From the eastern extension of the Teal Lake trough the main bedrock valley continues eastward into sec. 32, T. 48 N., R. 26 W., following generally the present course of lower Carp River. The exact course of the drainage-lines and the altitude of the bedrock surface are not known because of the lack of drill holes and bedrock outcrops. East of sec. 34 the main incising might possibly follow one of three courses: (1) the Morgan Creek drainageway, (2) the Carp River drainageway, or (3) a course between these. Inadequate information prevents the designation of the most likely course. The Morgan Creek drainageway is on an area of resistant bedrock, but it is a likely course if the Teal Lake scarp continues this far east. The present Carp River channel is on the nonresistant Siamo slate, but there are high bedrock altitudes along this channel about half a mile east of the report area. The third postulated course, between Morgan Creek and Carp River, would be on the nonresistant Wewe slate, but at present the area is a highland owing to glacial filling.

PARTRIDGE CREEK AREA -- secs. 8, 9, and 15, T. 47 N., R. 26 W.

The major bedrock valley along the lower part of the present course of Partridge Creek, southeast of Negaunee, has a north fork heading in the hilly area in the NE¼ sec. 7, T. 47 N., R. 26 W., and a south fork heading near the NE cor. sec. 19. This south fork trends due north through a steep-sided valley for about a mile and then turns northeastward to join the north fork near the center of sec. 8, east of a dissected low tableland. The drainage lines continue southeastward into a basin in the S½ sec. 9, then through a narrow channel in the N½ sec. 15 into a basin occupied by Goose Lake, and from there southeastward through a very narrow steep-sided gorge out of the synclinorium. No definite drainage pattern can be defined along this valley east of the center of sec. 8 owing to the lack of positive data on the buried bedrocks. However, differences in lithological erosion resistance and faults appear to govern the course of the south fork and its exit from the synclinorium through very resistant rocks. In the vicinity of the west end of Goose Lake, there are prominent faults, some of which have a definite effect on the drainage pattern. Seismic surveys by the Michigan College of Mining and Technology indicate the lowest bedrock surface in the area to be 1.165 feet above mean sea level several hundred feet southeast of Goose Lake.

RICHMOND MINE AREA -- secs. 26 and 27, T. 47 N., R. 26 W.

A highland area in the central part of secs. 22 and 23 is the head of a buried valley which trends southward along the east line of sec. 27, near the basal contact of the Negaunee iron-formation. This valley undoubtedly has a gradient toward the same drainage system (beyond the district) as the present Partridge Creek system. The lowest bedrock altitude in the district, 1.087 feet above mean sea level, is reported in a drill hole in the SW¼ sec. 26.

A western fork of the above described valley system passes through a gap in granitic and gneissic rocks via a northwestward-trending ravine south of the Richmond mine, and drains a basin in sec. 28. From the middle of the basin several smaller valleys extend into the highlands surrounding it, with the most prominent being those short east-west valleys that parallel the Palmer fault in the S½N½ secs. 28 and 29.

WARNERS CREEK AREA -- secs. 17, 19, 20, 29, 30, and 31, T. 47 N., R. 26 W., and secs. 23, 24, 25, and 26, T. 47 N., R. 27 W. Figure 3 shows the bedrock valley system developed on the south and eastern sides of the Negaunee "structural" Basin. Contouring has outlined the main sections of the valley and its branches, but details within the valleys are not adequately defined. The main channel roughly parallels and coincides with the present valley of Warners Creek from north of the village of Palmer to the point where it leaves the report area in the NE¼ sec. 31, T. 47 N., R. 26 W. Additional drill hole information and geological exploration are needed to complete the bedrock surface details of this valley system.

Geology of Unconsolidated Deposits

Pleistocene (Glacial) History

After the bedrock had been eroded to roughly the present altitudes, the Pleistocene epoch, or ice age, ensued. During this epoch large continental glaciers or ice sheets spread over much of the North American continent. These glaciers advanced when the snow and ice accumulated and wasted when the snow and ice melted. Factors such as differential accumulation, melting of the ice, and topographic control of the glaciers1 movements produced irregular shapes along their periphery, causing lobes or tongues of ice to project outward from the areas of accumulation. This district, owing to its high latitude and moderate altitude, was undoubtedly overridden by ice more than once. The ice sheet of the last, or Wisconsin stage, growing southwestward from the center in Labrador, advanced through the basins of Lake Superior and Lake Michigan in two great lobes directed roughly west-southwest and southward respectively. Two or more advances of the ice over the district are indicated by the direction of the striae carved on the bedrock, by the elongated axes of certain eroded bedrock masses in the direction of the ice movement, and by the orientation of the tails of glacial materials deposited in the lee of bedrock knobs.

The most vigorous glacial action occurred when, the ice advanced in a general S. 60°-65° W. direction. This was not the latest advance, nor the earliest, as later striae trending S. 40° W. to west were observed over the others. Older striae were also observed -- several trending south are near the SE cor. sec. 13, T. 47 N., R. 26 W. and several trending N. 60°-65° W. are north of the Palmer fault in secs. 23, and 25, T. 47 N., R. 26 W.

The principal effect of the ice age on topography appears to have been a leveling of the land surface by filling the depressions rather than erosion of the high masses. Glacial deposits consisting of unconsolidated materials of varying sequence and ranging up to 200 feet or more in thickness occur in the deeper and larger bedrock valleys and elsewhere they occur as a thin cover over the bedrock. Deposits of two or more ice advances are common, and the interglacial erosion of these deposits is indicated in several areas by reworked till and outwash deposits overlain by a younger till.

Surficial Materials

Figure 4 shows the pattern of the surface materials in the area which except for bedrock outcrops may be roughly classified into three types: till, outwash and lacustrine deposits.

The till is primarily in the form of ground moraine, and consists of unsorted to roughly sorted mixtures of glacial sand, gravel, and clay, usually associated with cobbles and boulders, deposited from the glacier either on land or in water. In most glaciated areas the farthest advance of the glacier is marked by a ridge, called a terminal or recessional moraine, where the load was dumped. In this area there are no large recessional moraines, although in a few places some high knolls of till suggest remnants of intermediate advances and recessions. In general, the surface is moderately rolling to flat in those areas where till occurs on valley fill. Where till occurs as a veneer over bedrock the land form roughly reflects the bedrock surface. In this report the till is subdivided into two units -- one, unmodified till, that is, till whose surface expression does not resemble bedrock topography; and the other, rock-controlled till, that is, till whose present surface expression resembles the bedrock topography, which normally lies at a shallow depth. This division of the till into two units was noted by Thwaites (1946. pp. 45-46), and in this district the division was made because the ground-water characteristics of the two types of areas are different. The unmodified till normally serves more or less as a permanent ground-water reservoir and the rock-controlled till serves only as a temporary reservoir. Rock-controlled till occurs in highland areas, generally around areas of large or numerous bedrock masses. The unmodified till is present both in the highland areas and in the valleys.

Outwash consists of sorted and stratified sand and gravel with cobbles and some boulders, laid down by streams and meltwater from the glacier. The major areas of outwash are characterized by fairly large flat plains or aprons. In some places these plains are dimpled with pits caused by melting of blocks of ice deposited with the sand and gravel. This form is called a pitted outwash plain. Locally long, narrow, winding ridges of sand, gravel, and boulders, called eskers, are present. Eskers in this area are about 200 to 1,000 feet long and rise 10 to 30 feet above the surrounding land surface. These ridges were formed by deposition of sand and gravel in streams, presumably entrenched, within or below the glacier. Outwash occurs also in the form of kames, knolls of irregular shape containing roughly sorted sand and gravel deposited in potholes near the edge of the glacier. Other land forms common to the outwash deposits are flat-topped terrace remnants along the former drainageways, and sluiceways, which are fairly long, narrow, and rather steep-sided valley channels having either small (misfit) streams or no streams at all. The terrace remnants were formed by erosion of the surrounding outwash, and the sluiceways are valleys scoured out by glacial meltwaters.

The lacustrine deposits, composed predominantly of clays, formed in glacial lakes, possess the characteristic topographic form of a plain resulting from the flat-lying beds.

Till

The tills possess an irregular lithology and structure and this non-uniformity is the result of the mode of deposition from the glacier. However, certain types of till predominate in the area. The most common type is the sandy and gravelly brown to yellowish-brown till with a relatively small percentage of fine material and which normally contains cobbles and boulders. It is highly variable in composition, and possesses at places a poorly developed sorting, and stratification. Very coarse till deposits, in which boulders are the dominant constituent, occur at several places, such as in the NE¼ sec. 7, T. 47 N., R. 27 W., in the NE¼NE¼ sec. 10, and in the NW¼ sec. 11, T. 47 N., R. 29 W. Another type of till has the characteristic deep red stain of iron oxide owing to the presence of considerable amount of red clay. This till probably has been formed by materials obtained locally from the iron-formation. It occurs at Summit Mountain (sec. 24. T. 47 N., R. 27 W.) and in the surrounding area. Another type of till, occurring in small areas, is composed of a slightly sandy and gravelly medium to light brownish red silty material, which appears to be a mixture of the other two types of till.

At a number of places the composition and structural features of the till resemble those of outwash deposits so closely that it is difficult to distinguish between the two. In fact, some deposits are actually a "borderline material." This condition exists both in materials with and without cobbles and boulders. These areas have been mapped on figure 4 as either outwash or till according to the mapper's judgment. Fairly well sorted sand and gravel which is a "borderline material" occurs in the vicinity of the NW¼ sec. 7. T. 47 N., R. 27 W., in the central and east central parts of sec. 2, T. 47 N., R. 26 W., and along the west line of sec. 17, T. 47 N., R. 26 W. In all these localities the "borderline material" has been mapped as outwash, but near the W½ cor. sec. 17, T. 47 N., R. 26 W. it appears to be a crevasse-filling material. In several areas this borderline material overlies outwash sand and gravel as a thin layer of sandy, stony soil which usually contains some cobbles and. boulders.

Outwash

The outwash is stratified fairly clean coarse sand, gravel, cobbles, and boulders; the general lack of concentrations of fine materials (clay and silt) is characteristic. It is not uniformly sorted and stratified throughout the district, although locally there may be some uniformity, especially downstream from the source of the transporting media. Near the source the materials are very coarse and tend to be heterogeneous; the sorting and stratification are generally very poor and beds of sand and gravel are interlayered with many cobbles and boulders. Boulder beds are widespread, occurring at both high and low altitudes throughout the area, generally immediately below the land surface. Despite the great amount of exceedingly coarse material in the outwash, deposits of clean sand and gravel predominate. The individual beds in the outwash aprons are not continuous over large areas. Both gravel and sand horizons are composed of innumerable small lenses, generally cut off and lying as steeply dipping foreset beds. Crossbedding and marked differences in the degree of sorting of the various beds of sand and gravel are very notable features. These characteristics indicate the rapidly changing conditions of deposition that existed when these outwash materials were deposited from the heavily laden meltwaters escaping from the ice fronts.

Lacustrine deposits

The glacial lake deposits consist of two types: one is the varved and massive clay below the outwash present in SE¼ sec. 1, T. 47 N., R. 28 W., and in NE¼ sec. 9, T. 47 N., R. 27 W.; the other is an impure calcareous marl occurring in depressions south of North Lake in the SE¼NE¼ sec. 2, T. 47 N,, R. 28 W. and beneath the swamp deposits in the subsidence area of the Morris mine in the SE¼ sec. 1, T. 47 N., R. 28 W. At this latter locality the marl is fossiliferous. Thin beds of lacustrine clays, between outwash sands and gravels overlain by till, are at the Lake mine subsidence area in the SE¼SE¼ sec. 10, T. 47 N., R. 27 W. These glacial lake deposits occupy a very small percentage of the area.

Postglacial deposits

SWAMP-TYPE DEPOSITS

Swamps cover a considerable part of the area and occur throughout a wide range of altitude. They can be classified into two basic types: (1) those in the morainal areas, having a surface deposit of decayed vegetal debris arid boulders underlain by till, and (2) those in the outwash plains, generally at lower altitudes. The latter class contains several types of surface deposits which may be (a) sand and gravel, (b) decayed vegetal matter and muck, resembling muskeg, (e) peat, usually underlain by outwash, and (d) impure swamp or bog deposits which are normally interbedded with or underlain by sand and gravel. On figure 4 one symbol has been used to designate this type of deposit regardless of the above classification.

LACUSTRINE DEPOSITS

Postglacial lake deposits consist primarily of bedded sand and gravel, which locally include decayed vegetation. Examples of this type of deposit are on the east shore of Teal Lake, in the drained area in S½NE¼ sec. 2, T. 47 N., R. 27 W., and along the former beaches and bed of North Lake. Large, flat, water-worn beach boulders occur on the shore of the southeastern tip of Tilden Lake and along the northeastern shore of Teal Lake. Like the glacial lake deposits they form a very small percentage of the area.

ALLUVIAL DEPOSITS

The flood-plain deposits of present streams consist mainly of bedded sand, gravel, silt, and muck, occurring in narrow strips along the drainageways. They form an extremely small percentage of the area and, therefore, have not been mapped.

Effect of Bedrock Topography on Deposition of Glacial Materials

In areas of low bedrock altitude the pattern of deposition of glacial materials in land forms is similar to that in other glaciated areas. However, in the bedrock highlands the land forms and normal pattern are absent or incomplete.

Highlands

Large masses of bedrock, where present as highlands, were obstacles which prevented the easy movement of the ice at the bottom of the glacier with the result that a form of stagnation of the lower part of the ice occurred. This stagnation greatly influenced the deposition of the glacial materials in the following ways: (1) where massive resistant rock rose to a higher level than the surrounding area, the materials were deposited as a thin plaster which probably was removed with each successive ice advance; (2) where the ice movement was perpendicular to the bedrock valley the small ratio of the width to length and depth hindered the ice from removing or reworking previous deposits; (3) where the narrow outlets to the bedrock valleys acted as dams the materials were not eroded; and (4) where large bedrock masses acted as shields the terraces were neither removed nor covered with till.

Thin plasters of till on the bedrock or rock-controlled till are shown on figure 4 in, (1) an east-west band along the northern margin of the district; (2) the Humboldt-Clarksburg area, (3) the Negaunee Basin area immediately south of Negaunee and Ishpeming, and (4) the area north, west, and south of Goose Lake. The largest area of rock-controlled till is the northern half of the Negaunee Basin around Summit Mountain.

Many of the valleys parallel to the north limb of the synclinorium were filled with till and lacustrine materials from the first stages of glaciation, but due to the lack of space in which the ice tongues might maneuver little scour or erosion took place on successive advances. Logs of drill holes at the Blueberry mine area in sec. 3, T. 47 N., R. 28 W., and the Athens mine area in sec. 6, T. 47 N., R. 26 W. indicate the older tills were not removed by subsequent action on the north sides of the bedrock valleys.

Normally large surficial topographic basins filled with the glacial deposits and having an outwash or muck and peat cover have broad outlets, but at several places, such as in the N½SE¼ sec. 4, T. 47 N., R, 27 W., in the center of the NW¼ sec. 15, T. 47 N. , R. 26 W., and at the outlet of Goose Lake in the center of the NW¼ sec. 24, T. 47 N., R. 26 W., the outlets between the bedrock or bedrock-controlled till highs are narrow. This appears to be the result of a broad basin developed in the bedrock with a ravine type outlet, or a depression in the basin deeper than the outlet, so that damning of the outlet caused filling and prevention of further erosion of the glacial deposits in the basin. A small local outwash area in the NE¼ sec. 21, T. 47 N., R. 26 W. was developed by damming a southeastward-draining valley through a bedrock highland. Such rock-rimmed basins are common in the highlands of the Negaunee “structural" Basin and form the site of some large lakes, such as Lake Sally, Lake Miller, and Tilden Lake.

South of Partridge Greek the large flat highland-, covered with unmodified till except in the central and western part of sec. 16, T. 47 W., R. 26 W. is rather unique in that it appears to be a large outwash terrace equivalent to the terrace remnants at the eastern edge of Negaunee and the southward extension of a large terrace to the north in the N½ sec. 34, T. 48 N., R. 26 W. This highland is bordered by till on all sides although the till on the south side resembles outwash. The lack of till cover over the outwash in the central and western part of sec. 16, may have been caused by the resistance of the buried high intrusive masses, to the northeast in sec. 10, to the ice advance.

<u>Lowlands</u>

In areas of low bedrock altitudes little resistance to the forces of glaciation occurred and deposits from several stages of ice movement remain. Remnants of some of the last stages are recessional moraines, sluiceways, and eskers. Evidence of the older stages are terraces, terrace remnants, and till-covered outwash plains that have been exposed by erosion or excavation.

Land-form Development in Areas of Low Bedrock Altitudes

Leverett, (1917, Pl. 1) indicates two major morainal ridges in the central part of the district. The westernmost morainal ridge trends southeast through T. 47 N., R. 28 W. with a limb extending eastward into T. 47 N., R. 27 W. A plain of sand and gravel occurs between these limbs. The easternmost morainal ridge trends essentially east-west through the N½ T. 47 N., R., 27 and 26 W. with a narrow branch extending south to the southwest part of T. 47 N., R. 26 W. where it disappears near the south-central part of the township.

The detailed map indicates four points of dissimilarity with the general pattern shown on Leverett's map. (1) The westernmost morainal ridge trending across T. 47 N., R. 28 W. continues southeast of the report area. Although considerably dissected this ridge can be traced through the SE¼ sec. 11, secs. 12, 13, 14, 23, and 24, T. 47 N., R. 28 W., and secs. 7, 8, 9, 16, 17, 18, 19, and 20, T. 47 N., R. 27 W. to a junction with the eastern limb of the western ridge. (2) The area of outwash deposits between the morainal ridges is considerably smaller. (3) The line of contact between the outwash and till deposits is not as sharply alined as is indicated. The transition zone between the till and outwash is often wide with isolated deposits of both till and outwash, and in other parts the till is deeply serrated and often cut out and replaced by outwash. (4) The areas where bedrock is close to the land surface are larger and new outlying areas have been added.

In addition to the morainal ridges other land forms related to glaciation in the district are: (1) ground moraine covering bedrock hills of low altitudes, (2) outwash plains, (3) terraces, (4) eskers, kames and crevasse filling, and (5) sluiceways. Ground moraine covering bedrock hills of low altitude has the same topographic characteristics as that for the highland areas, although greatly subdued. Typical localities having these characteristics are along the ridges of the bedrock valleys south of the Blueberry mine.

<u>Outwash plains</u>

In the area east and south of Negaunee two large outwash plains probably existed in Pleistocene time at altitudes of about 1,400 and 1,300 feet. Interglacial erosion eroded and partially destroyed the high-level terraces and formed successively lower ones. Evidence supporting the existence of these former large outwash plains are: (1) widespread remnants, some fairly large, of terraces at these altitudes; (2) presence of large sand plains to the south and east of the iron-bearing synclinorium, in the Goose Lake area and extending many miles southward and eastward; (3) presence of sluiceways, indicating the areas of concentrated meltwater flow which eroded the higher level plains and terraces; (4) presence of successively lower outwash terraces below the 1,400 and 1,300-foot terraces; (5) the common occurrences of outwash remnants at various levels under a thin till cover, indicating terraces and outwash plain remnants in various stages of erosion before burial by the till; and (6) the 1,300-foot outwash terraces generally contain fine materials of similar lithology to the 1,400-foot outwash.

Terraces

Terraces and terrace remnants are common features in the eastern section of the district. In the western section north of Humboldt in the northern part of T. 47 N., and the southern part of T. 48 N., R. 29 W. there are several sets of step-like terraces at progressively higher altitudes to the north, and in secs. 3 and 4, T. 47 N., R. 28 W. a few terraces less than four feet high have been mapped. However, near Ishpeming and especially south and east of Negaunee many large terrace remnants are found. Much of the northern part of the city of Ishpeming consists of terrace remnants of an outwash plain which has a top altitude of 1,460 feet. The greater part of the developed area of Negaunee and the area east of Teal Lake consists of outwash whose top altitude is 1,400 feet. Remnants of lower terraces are found east of Negaunee in the Carp River basin, in the Partridge Creek basin and along Warners Creek near Palmer. The locations of the major terraces are listed in tables 6 and 7, and are shown on figure 4.

Sluiceways

Sluiceways are common in the valley lowlands west of Ishpeming. They mark the location of glacial streams usually of considerable size concentrated in a small area. In many instances they are represented on figure 4 as the long narrow extensions of swamp-type deposits leading into the outwash deposits. The locations of some of the major sluiceways in the district are shown in table 8.

Kames, eskers, and crevasse fillings

These topographic forms are the deposits of sediment laden glacial streams of water in and under the ice. Table 9 shows the locations of some of these topographic forms.

Subsurface Materials

The continuity of the Quaternary subsurface materials and the general sequence of deposition were studied by the preparation of cross sections based on logs of drill holes. Some of these cross sections were compiled using strip logs containing the actual drilling samples. However, most were prepared from written logs of diamond drill-hole explorations and water wells. Many of these logs, especially those of the diamond drill-hole explorations, are incomplete or unreliable. Comparatively few logs contain any detailed description of the unconsolidated materials; most of them give only the total thickness of these deposits. Therefore, correlation of strata from hole to hole is generally not possible. Information for this study is available only in limited areas. Because of the difficulties listed above a complete study of the Quaternary deposits was impossible.

Table 10 lists the typical sections of subsurface material that may be found in particular areas (see locations on figure 2).

Sequence of Deposition

Owing to the changing conditions that existed in the ice age, the structure of the Pleistocene deposits is extremely complex and the materials differ from place to place and even in small localities. Therefore, the sequence of deposition of the Quaternary deposits cannot be satisfactorily explained. However, it appears to have occurred in the following order:

1. Basal till composed of sand, gravel, boulders, and clay is apparently the oldest deposit. The basal section is usually coarse and contains some fairly clean lenses of sand and gravel. The upper portion contains finer materials in the Athens and Maas mines area, West Ishpeming. and parts of the Morris mine area. This till is usually red, but is gray in the Humboldt area and in some parts of the Morris mine area.

2. The succeeding deposits are a series of varicolored fine sand, silt, and clay beds, probably of lacustrine origin. In the Morris mine area the deposits may have either a high percentage of red clay or coarse granular materials containing little clay. The small areas in which these materials are found indicate that there probably was little continuity of the lakes or ponds in which they were deposited.

3. Outwash sand, gravel, cobbles, and boulders overlie both the above types of deposits. These materials are usually fine at the base and coarse at the surface, contrary to the normal sequence. In the Mary Charlotte mine cave in SW¼NW¼| sec. 8, T. 47 N., R. 26 W. two peat beds are interlayered with the outwash.

4. A thin section of gray to white lacustrine clay and marl is present in the Morris mine and North Lake areas. In the Lake mine area thin beds of red and gray lake clays are interlayered with the outwash.

5. A later tan to brown sandy and gravelly boulder till normally occurs as a thin mantle. In the Tilden mine area outwash occurs over the later till. However, inasmuch as this was observed only in one place it is not listed as a major unit in the succession.

6. Recent muck, peat, sand, and gravel of alluvial lacustrine, and swamp deposition are the latest deposits.

This order of deposition is a generalized sequence obtained by observations of deposits in the report area. Undoubtedly there were cycles of deposition overlapping each other, interfingerings of different types of deposits, and also contemporaneous deposition of different types in different areas.

Summary

The geologic formations of the Marquette district consist of pre-Cambrian metamorphic rocks overlain by unconsolidated Pleistocene (glacial) and Recent deposits. The pre-Cambrian rocks are composed of a thick Huronian series of beds predominately of sedimentary origin lying between a northern and southern complex of gneiss, granite, schist, syenite, and peridotite. The Huronian rocks consist mainly of slates, quartzites, schists, conglomerates, graywackes, cherts9 dolomite, and basic intrusive rocks. Their history is complex, with many unconformities. These beds occur in a west-trending canoe-shaped synclinorium which extends from the shore of Lake Superior near Marquette through the Ishpeming-Negaunee area westward to Lake Michigamme, where the structure opens into a broad basin. The structures within the synclinorium are extremely complicated, with many tight folds, faults, and intrusions of diabasic rocks.

The topography of the surface of the pre-Cambrian rocks is controlled by the differential erosion resistance of the various bedrock strata and by structural features. It was developed during a long interval of geologic time. Remnants of a peneplain surface are present but later uplift gave rise to the present stage of a youthful erosion surface, now mostly covered by glacial drift. The drainage pattern is complex arid depends on the bedrock strata and structure. The region is a headwater area with drainage to both Lake Superior and Lake Michigan. The total bedrock relief within the area of investigation is 783 feet, but in general the local relief of the bedrock is moderate, the largest valleys being about 200 to 300 feet deep.

The Pleistocene (glacial) deposits have filled the deeper bedrock valleys and occur as a mantle over the remainder of the area, reducing and modifying the surface relief. The greatest known thickness is 285 feet. A predominant characteristic of the deposits is the coarseness of the materials. These deposits consist mainly of till (unsorted glacial debris), outwash (stratified sand and gravel), and lacustrine deposits (lake clay and sand). The till is the dominant surface material, and it occurs throughout the area as ground moraine. There are at least two tills present. The older till has been encountered in many drill holes and is exposed in an excavation at the Lake mine. The younger till characteristically contains very little clayey material and occurs as a very thin mantle over outwash in many places throughout the area. The outwash and lacustrine deposits occur in the broad basins of filled bedrock valleys both at the surface and at depth.

Location	Altitude	Remarks
T. 48 N., R. 29 W.		
NE¼ sec. 35 and NW¼ sec. 36	1,550	Stairlike
T. 48 N., R. 26 W.		
N½S½ sec. 1	1,400	NE of Teal Lake
S½ sec. 33	1,310-1,300	
SE¼ sec. 33	1,360-1,300	
N½S½ sec. 34	1,320-1,280	
secs. 35 and 36	1,280	
T. 47 N., R. 28 W.		
secs. 1, 2, 11, and 12	1,560	Large pitted outwash plain extending southward into an area of unmodified till.
secs. 3, 4, 5, 8, and 9	--	Several are stairlike -- 4 feet high. The largest area in secs. 3 and 4 is a pitted plain in several localities.
T. 47 N., R. 27 W.		
SW¼SE¼ sec. 4	1,460	30-50 feet above Carp River
T. 47 N., R. 26 W.		
secs. 1 and 2	1,300	
sec. 16	1,420	
NE¼ sec. 21	1,460	

Table 6. Location and altitudes of some major terraces.

Along the northern part of the district, especially west of Ishpeming, large plains of poorly sorted outwash, containing many cobbles and boulders, are common. In the southern part of the area west of Ishpeming and east of Negaunee the outwash is generally well sorted, consisting mainly of sand and gravel. The gradation of the surface materials, their structure, the evidence of terraces and sluiceways, and the general slope and appearance of the land forms indicates that the source of this surface outwash was to the north and that the latest glacial meltwaters spread primarily to the south and east when they entered the synclinorium. Because the material is finer grained with depth it is probable that the outwash was deposited by an advancing mass of ice at some distance away, but as it came closer to the site of deposition the materials became coarser with each additional accretion from the meltwaters.

GROUND WATER

Source

Ground water has been defined by Meinzer (1923, p. 38) as "that part of the subsurface water which is in the zone of saturation." It is the water that supplies wells and springs. Its principal source in this district is the rain and snow that falls on the immediate area.

That precipitation is adequate to meet all demands is shown by the fact that the average rainfall of 31.1 inches contributes annually about 540 million gallons of water for each square mile of land surface in the district. Of this, part runs off directly into the streams, a part leaves as evapotranspiration, and the remainder recharges and is stored in the ground-water reservoirs to be later discharged by springs or by evapotranspiration. Although the supply of ground water generally varies with the amount of precipitation, other factors also control the rate of recharge. If the air temperature is very high the rate of evaporation materially decreases the potential supply of ground water. If, on the other hand, the temperature is so low that the ground is frozen, an unusually high percentage of water, finding its descent blocked, runs off directly into the surface drainage.

Location	Altitude	Remarks
T. 47 N., R. 26 W.		
S½SE¼ sec. 8	1,360	
N½NE¼ sec. 9	1,400	
SE¼SW¼SW¼ sec. 20	1,300	Till mantles underlain by outwash
S½ sec. 24, sec. 25 and E½ sec. 26	1,220-1,210	
S½NW¼ sec. 27	1,280-1,260	
W½ sec. 29	1,300	
Near N¼ cor. sec. 31	1,300	Underlain by outwash
Near W¼ cor. sec. 31	1,300	

Table 7. Locations of till-covered terraces.

Location	Trend	Remarks
T. 48 N., R. 29 W.		
E½ sec. 34	S	
SE¼	SW	
T. 48 N., R. 28 W.		
SE¼SE¼ sec. 34	W	Boulder bottomed
SE¼SW¼ sec. 36	SE	Some boulders
T. 48 N., R. 26 W.		
NE¼ sec. 35	SW	
T. 47 N., R. 29 W.		
SE¼NE¼ sec. 12	NE	Boulder bottomed
N½ NE¼ sec. 13	SW	Boulder bottomed
T. 47 N., R. 28 W.		
N½ sec. 1	SW	Boulder bottomed
NE¼ sec. 11 and NW 1/3 sec. 12	S-SW	Forked sluiceway
W½NW¼ sec. 15	S-W	
T. 47 N., R. 27 W.		
NE¼SE¼ sec. 5	SW	Boulder bottomed
SW¼SE¼ sec. 5	SW	do.
SE¼SW¼ sec. 9	NE	do.
N½ SE¼ sec. 17	N	do.
E½SE¼ sec. 18	N	do.
S½NW¼ sec. 27	NW	do.
T. 47 N., R. 26 W.		
NW¼NE¼ sec. 5	Indefinite	Scattered boulders
S½ sec. 8	NW and W	Boulder bottomed
NW¼ sec. 17 and SW ¼ sec. 8	NE	
E½ sec. 19	S	Along Warners Creek
sec. 20	SW	Along east fork of Warners Creek
SE¼ sec. 24	SE	
SW¼ sec. 30	E	

Table 8. Locations of sluiceways.

Location	Trend	Length (ft)	Width (ft)	Height	Remarks
T. 47 N., R. 27 W.					
NW ¼ sec. 5	N-NW	1,000	10-200	15	Esker
N½S¼NE¼ sec. 5	NE	400	20- 50	15	Esker
T. 47 N., R. 26 W.					
SW¼NW¼ sec. 8	N-S	--	100	15-40	Crevasse -filling
S½SE¼ sec. 8	N-S	500 to 600	50-300	50	Kame
S½SE¼ sec. 8	N-S	400	15- 25	15-25	Kame

Table 9. Locations of eskers, kames, and crevasse fillings.

Location	Material	Thickness (feet)	Remarks
Humboldt area, Sec. 35, T. 48 N., R. 29 W.	Outwash	65	Section is based on samples of 8 churn drill holes.
	Lacustrine -- gray, tan, brown, fine sand, silt and clay	20- 30	At places outwash extends from basal till to land surface.
	Till -- sand, gravel, clay	10	
Blueberry mine area, Secs. 3 and 4, T. 47 N., R. 28 W.	Outwash	35	Typical section is in NE¼ sec. 4. South and east of this area basal till is absent, and outwash is 35 to 40 feet thick.
	Lacustrine	0	
	Till	10- 25	
North Lake and Barnes-Hecker mine area, Sec. 2, T. 47 N., R. 28 W.	Outwash	100-125	Many logs indicate a very irregular sequence of deposition. A northeast-trending interglacial valley passing through center of sec. 2 is indicated where
	Lacustrine	0	
	Till	0- 85	

			basal till is absent.
Morris mine are, S½ sec. 1, T. 47 N., R. 28 W.	Muck and peat	0- 10	Samples from many closely spaced holes were studied. Sometimes lacustrine material has definite red banding near base and in upper section. Sometimes basal till is gray with lenses of coarse material.
	Outwash -- sand and gravel	40	
	Lacustrine -- red, gray, brown fine sand, silt and clay varved with hardpan lenses.	60- 80	
	Till -- reddish-brown, clayey with boulders	4- 60	
West Ishpeming area, Secs. 4 and 9, T. 47 N., R. 27 W.	Muck and peat	0- 10	Section is based on many logs and some samples. Bedrock topography is very rough.
	Outwash, sand and gravel	8- 40	
	Lacustrine -- fine sand, silt, red and gray clay	60- 70	
	Till -- red clay, sand, gravel, boulder hardpan	7- 60	
Northwest Ishpeming area, Sec. 3, T 47 N., R. 27 W.	Muck	0- 10	Bedrock topography is rough.
	Outwash sand and gravel	40	
	Lacustrine	0	
	Till -- gravel, hardpan, boulders	5- 70	
Mather mine A shaft area, sec. 2, T. 47 N., R. 27 W.	Muck and peat	0- 5	Muck and peat occur only along west line of Sec. 2. Bedrock topography is moderate.
	Outwash, sand and gravel	30-120	
	Lacustrine	0	
	Till -- stony and bouldery hardpan	0- 12	
Athens mine area, sec. 6, T. 47 N., R. 26 W.	Outwash, sand and gravel	5- 15	Lacustrine materials range from 35 to 50 feet in thickness in northwest part of valley and are absent in southeast part.
	Lacustrine -- fine sand and red clay	0- 50	
	Till -- red sand, gravel, clay	15	
Maas mine area, Sec. 31, T. 48 N., R. 26 W.	Outwash -- sand and gravel	60-130	Outwash becomes finer-grained with depth.
	Lacustrine -- red clay, and gravel and hardpan layers, finer-grained than the usual till	70-120	Lacustrine materials occur in irregular lenses.
	Till -- red clay, sand and gravel, boulders and hardpan	10- 40	Till is generally in northern and central parts of area.

Table 10. Typical sections of subsurface materials by localities.

Occurrence

Most of the subsurface water is contained in the zone of saturation. This is a natural water reservoir formed in the innumerable interstices of both the unconsolidated deposits such as sand and gravel and in the openings of consolidated formations. In the consolidated rocks such as slates, iron-bearing formations, and quartzites, some water occurs in the minute crevices between the crystalline grains, but the portion of greatest importance to mining occurs in vugs and in fractures, particularly joints and openings along bedding planes.

Generally, ground water is moving slowly from areas of intake to points of discharge. The movement may range from a few feet a year to a few feet a days except at points of concentrated discharge where it is more rapid. Ground water occurs under either water-table or artesian conditions. Under water-table conditions it is unconfined, and the upper surface of the saturated zone, which is at atmospheric pressure, is called the water table. Under artesian conditions it passes beneath an impermeable bed and is confined under greater than atmospheric pressure. In certain areas within the Marquette district local stratification of the glacial drift causes ground water to exist under artesian conditions. These conditions prevail locally, but not in large areas, although scattered wells throughout the entire district show evidences of ground-water confinement. In bedrock the occurrence of the water largely depends on the structure of the bedrock and the altitude of the water at the area of outcrop, but generally, where first encountered, the water exists under artesian conditions.

Where the water table exists either in the bedrock or glacial overburden, it seldom has a plane surface like that of a surface reservoir or lake. In general, it has irregularities comparable with the land surface but more subdued. The water table generally lies in the glacial drift not far above the bedrock surface where the bedrock hills extend above the present surface drainage level. Where the bedrock is below the present surface drainage, the water table in the glacial drift slopes gently to the surface drainage.

The principles of the occurrence and movement of ground water are discussed in detail by Meinzer (1923a, 1923b), Tolman (1937), Wenzel (1942), and others. The interested reader is referred to their works for additional information.

Where a water-bearing formation is exposed directly at the land surface ground water occurs tinder water-table conditions in the voids, or interstitial spaces, and the formation serves primarily as a storage reservoir. The property of having interstices or voids is called porosity and is expressed quantitatively as the percentage of the total volume that is occupied by voids -- that is, that part which is not occupied by the solid rock material (Meinzer, 1923a, pp. 2-3). In granular material or unconsolidated deposits, porosity depends mainly on the uniformity of grain size, shape, and packing arrangement of the individual fragments, not on the size of the particles. A sand composed of well-rounded particles of uniform size normally has a higher porosity (25 to 45 percent, depending on packing) than a poorly sorted gravel composed of particles of different sizes and shapes (generally less than 15 percent). Clays, although they are very fine grained, usually have a high porosity (in some cases more than 50 percent). The bedrock, although considered rather massive, has an over-all porosity equal to that of poorly sorted gravel (about 5 percent).

In the zone of saturation all the interstices are filled with water and as the water table is lowered the interstices are partially emptied. Molecular forces (cohesion and adhesion) counteracting the force of gravity cause water to be held on the surface of the individual particles. Therefore, the quantity of water released from the interstices by lowering the water table is not as great as the porosity nor directly related to it. The ability of a rock to yield water is measured by its coefficient of storage, which is the quantity of water, expressed as a fraction of a cubic foot, that is released from a vertical prism of the material, 1 square foot in cross-sectional area, when the pressure head in the formation is lowered 1 foot. Where water-table conditions exist, the coefficient of storage is essentially equal to the specific yield -- the fraction of a cubic foot of water that will drain from a cubic foot of the saturated material. However, in this report the term "coefficient of storage” is used to refer to the storage characteristics of the district as a whole.

The water-bearing formations, in addition to functioning as a storage reservoir for ground water, also function as conduits for the transmission of the ground water from points of recharge to points of discharge. In an artesian aquifer the transmission function is more important than the storage. The ability of material to transmit water is measured by its coefficient of permeability, which can be expressed as the rate of flow, in gallons a day, that will pass through a cross-sectional area of 1 square foot of the material under a hydraulic gradient of 1 foot per foot at 60°F. The field coefficient of permeability is the same except that it is measured at the prevailing temperature of the ground water. The coefficient of transmissibility is the product of the field coefficient of permeability and the saturated thickness of the formation, in feet, and is expressed as the number of gallons of water a day that will pass through a vertical strip of water-bearing formation 1 foot wide and having a full height of the saturated part of the formation under a 1-foot-per-foot hydraulic gradient. It may be expressed also as the quantity of water, in gallons a day, that will flow through a section of the aquifer 1 mile wide under a hydraulic gradient of 1 foot per mile.

The coefficients of storage and transmissibility are the hydraulic characteristics of a water-bearing formation that govern the flow of ground water through the formation and the interference effects between wells. These properties are different in the glacial over-burden and in the bedrock, and may change within short distances in the same formation. Such differences are especially marked in the formations in the Marquette district. Methods for determining these coefficients of storage, specific yield, and transmissibility are discussed by Wenzel (1942, pp. 50-112), Theis (1935, 99. 519-524), Cooper and Jacob (1946, pp. 526-534), Ferris (1948), and others.

Water in Consolidated Rocks

Although the porosity of the bedrocks may vary considerably from one formation to another, only those pores which are larger than a certain size release water by gravity to any opening in the formation. That size varies with the shape of the pore and the mineral character of its walls, the temperature and chemical content of the water, and other factors. Even very small pores will transmit water under a hydraulic gradient when the rock is saturated, but only slowly. In the Marquette district the number and size of the pores differ from rock to rock, but in general very little water is transmitted through the pore structure of the rocks, because the pores are small or not interconnected. However, other openings, such as solution channels and fractures in the rocks give a formation as a whole some degree of permeability, so that it may transmit considerable water. Laboratory tests on cores of bedrock in the Lake Superior region indicate the permeability of the cores to range from 0.000003 to 3.3 gpd/ft^2 (see table 18). Field tests made by measuring the flow through the drifts in a mine and from drill holes indicate the permeability of the bedrock formations in place to range from 0.01 to 5.0 gpd/ft^2. No laboratory tests on the porosity have been made, but Van Hise and Leith (1911. p. 275) estimate the porosity of the soft ores of the Marquette district to average 35 percent. A more complete discussion on the flow of water in the bedrock appears under a later heading -- Ground-water movement in the bedrock.

Water in the Glacial Deposits

The unconsolidated deposits because of their relatively coarse grained, well-sorted character have a higher degree of interconnection of pore spaces and are therefore better adapted than the bedrocks to yield water to wells or drainage structures. Of these deposits only the glacial materials -- outwash, till, and lacustrine deposits -- are important water-bearing formations. The lithologic characteristics of these types of deposits are described in the section on the geology of the unconsolidated deposits

Outwash

Owing to both the large size and the high degree of interconnection of the pores of the outwash, especially the clean, well-sorted sand and gravel, this material has a very high permeability and can accept recharge, store water, and transmit water very readily. These characteristics make it an excellent aquifer where the saturated thickness is large. According to laboratory tests of samples of outwash from the Morris mine, Humboldt, and western Ishpeming areas the coefficients of permeability range from 60 to 6,000 gpd/ft^2.

Till

The till is very irregular in composition and structure and its variable character causes considerable range in hydraulic properties. The greater part of the till has poor sorting and irregularly shaped constituent particles -- properties which reduce its porosity and permeability. However, some types of till are more permeable, principally those which have rather uniform source materials such ass the predominantly sandy types, or the relatively clean sandy and gravelly types of the latest till, which usually occurs at or just below the land surface, or the non-clayey and non-silty layers of the deeply buried tills. Essentially only the cleaner, coarser-grained types are sufficiently permeable to yield water to wells or drainage structures. The wide range of the permeability of different types of till is shown by the coefficients of permeability determined by laboratory tests on many samples. The coefficients range from approximately 0.1 to 400 gpd/ft^2.

Lacustrine Deposits

The lake deposits are predominantly fine-grained sand and clay that are usually very well sorted. Because of their high degree of sorting they are porous and are definitely water-storing strata. However, due to their extremely small pore spaces they are poorly water-yielding. Exceptions are the very clean, coarse-grained sands included in these deposits. According to laboratory tests the coefficients of permeability of samples of the finer-grained silty and clayey deposits range from 0.1 to 70 gpd/ft^2 and those of the cleaner and coarser-grained sands range from 40 to 450 gpd/ft^2. In general, owing to the interlayering of various beds, these strata are water-storing but they transmit water very poorly. Beds that are predominantly clay actually function as impermeable members that retard the movement of water, thereby hindering or preventing recharge to adjacent deposits.

The Configuration of the Water Table

The water-bearing formations in the Marquette district constitute a large underground reservoir in which many million gallons of water are stored. The upper surface of this reservoir, the water table (the term “water table" is used even though locally the surface shown represents water confined under artesian pressure), represents the height to which the reservoir is filled. A contour map of the water table is a graphic representation of this surface and forms a basis for the study of the direction of movements rate of motion of the water, and zones of recharge and discharge; also it may indicate permeability differences of the various underlying saturated materials. The contours on the map (see fig. 5) indicate lines of equal altitude of water level or hydrostatic pressure. The direction of flow of the ground water is down gradient and at right angles to the contours. The contours are shown as solid lines where the data were adequate to define the water table. Dashed lines are used elsewhere in areas of inadequate data and where the altitude of the land surface is not accurately known.

Figure 5 is based on reported and measured depth to the static water level in all the observation wells accessible in September and October 1950. During this period the levels were low after steady declines through the summer and autumn from the high levels of the spring of 1950. The months of September and October were periods of deficient rainfall so that irregularities due to local recharge from precipitation were not important factors governing the water level, and in general the water table was in stable position. The major features of the water table change slowly over long periods of time, although the water levels in the wells are changing constantly owing to variations in rate of pumping of the wells, changes in barometric pressure, and recharge from various sources.

A comparison of the map showing the contours of the buried bedrock surface (fig. 3) and the map showing the contours of the water level (fig. 5) indicates that the ground-water reservoirs occupy all the bedrock valleys, and that these valleys are filled to a level as high as or higher than the surface stream drainage. In many places the ground-water reservoirs are continuous through low subsurface “drainage divides” from one bedrock drainage system to another. Most of the ground-water reservoirs of the district are connected with adjacent basins even though, in the following descriptions, they are discussed as separate basins or reservoir areas.

In the western part of the district along the north line of T. 47 N., R. 29 W., a ground-water reservoir extends from east of Boston Lake westward to the Escanaba River and includes part of the topographic basins on both sides of the river. In the NW¼ T. 47 N., R. 28 W. the same reservoir has a limb which drains southwestward past Lowmoor Lake to the Escanaba River through a low bedrock channel. The divide between the Escanaba River basin ground-water reservoir and the Carp River basin ground-water reservoir is essentially the topographic divide between the two river systems in secs. 4, 9, and 16, T. 47 N., R. 28 W.

The Carp River basin ground-water reservoir has several limbs and occupies several buried valley systems. One limb occupies the buried valley along the north flank of the iron-bearing synclinorium from east of Boston Lake in sec. 4, T. 47 N., R. 28 W., to the village of North Lake. High bedrock at this point terminates the eastward extension of the valley into sec. 4, T. 47 N., R. 27 W. However, the ground-water reservoir extends along the Carp River drainage southward from the village of North Lake through secs. 11, 12, 13. and 14, T. 47 N., R. 28 W., and eastward through secs. 18, 17, 8, and 9, T. 47 N., R. 27 W. An eastward, and northward-trending arm of the same ground-water reservoir drains the area in secs. 14, 15, 16, and 22, T. 47 N., R. 28 W.

Another ground-water reservoir system in the vicinity of Negaunee includes an arm in the bedrock valley south of the Mather A and B shafts, and an arm south of the Athens mine, all of which are tributary to the larger basin in the eastward extension of the Teal Lake trough. The highest levels in this basin are in the head-water areas near Lake Bacon at an altitude of 1,432 feet, and near Gunpowder Lake in sec. 12 at 1,455 feet. From these points the slope is downward to about 1,360 feet, at Negaunee, and the level slopes eastward to an altitude of 1,270 feet in the Carp River basin in sec. 33. T. 48 N., R. 26 W.

Cones of depression in the water table of the district are present near the Morris mine in sec. 1, T. 47 N., R. 28 W., near the Athens mine in SE¼ sec. 6, T. 47 N., R. 26 W., and near the Maas and Negaunee mines centering in the S½ sec. 32, T. 48 N., R. 26 W.

The cone of depression in the vicinity of the Morris mine is caused both by the withdrawal of water from the overburden and by entrance of water into the mine workings in the bedrock through subsidence zones. The rate of pumping within this cone of depression from wells averaged 1,650 gpm and from the mine averaged 1,350 gpm. The cone has expanded so that it now induces ground-water movement toward the point of withdrawal from more than a mile away. The cone extends under the Carp River from its source at North Lake to the center of sec. 12 about 10,000 feet downstream and includes part of the lower reach of Little Goldmine Creek in sec. 1. The present cone of influence covers an area of about 3 square miles, and it intercepts all the recharge available at its present level. However, if the cone were deepened or widened additional recharge would be intercepted around the edges.

The cone of depression in the vicinity of the Athens mine is caused by the entrance of the ground water into the mine workings owing to bedrock fractures developed by subsidence. Very little water is pumped from the overburden because the saturated thickness is negligible. The rate of pumping from the bedrock is approximately 400 gpm. This cone intercepts the ground-water flow in the S½ sec. 6, T. 47 N., R. 26 W., and a bedrock ridge through the center of the section inhibits the development of the cone to the north. The cone intercepts all the recharge to the west and south, and because of its depth prevents the normal flow of ground water eastward from this area into the bedrock valley in sec. 5. Water levels in this cone rise rapidly after heavy precipitation owing to the ease of percolation of water through the subsidence areas and broken ground in the SE¼ sec. 6.

The cone of ground-water depression in the vicinity of the Maas and Negaunee mines is superimposed upon a natural depression which existed because of the drainage of the basin by the Carp River. However, land subsidence has enlarged the cone and has permitted the entrance of a large quantity of water into the bedrock. The total rate of pumping from the two mines and one well in this area exceeds 3,000 gpm. In the vicinity of the Maas mine the shape of the cone is fairly well defined by water levels in observation wells; however, its westward extension toward Teal Lake and under the city of Negaunee as shown on figure 5 is mostly a matter of supposition.

Fluctuations of Water Levels

Ground-water levels seldom remain stationary. A rise of the water table may be a response to recharge of water to the aquifer, decrease in the withdrawals from wells, reduced atmospheric pressure, or combinations of these and other factors. A decline of the water table may be due to increased discharge of water from the aquifer, increased atmospheric pressure, or increased evapotranspiration. Annual cycles of fluctuation are caused by seasonal differences in both precipitation arid in the rates of evapotranspiration as well as other climatic conditions. In addition to the effect of the natural fluctuations of the water level, withdrawal of ground water through mining operations either by unwatering the overburden or by pumping from the mines produces long-term trends in a downward direction. Declines in ground-water levels resulting from extended dry periods should not be confused with the effects of efficient drainage structures in mine-water control programs.

The mining companies make depth-to-water measurements in wells on their own properties to determine the effectiveness of the surface pumping installations for unwatering the overburden above the mining operations. The depth-to-water measurements are made at biweekly or monthly intervals. Hydrographs of wells which are typical of the general conditions in four mine-water-control areas are shown on figures 6 and 7.

Morris Mine Area

Figure 6 shows types of typical fluctuations of water levels in wells in sec. 1, T. 47 N., R. 28 W., near the Morris mine. Test well 503 is located within the cone of depression caused by the surface pumping and the water level is also influenced by the downward percolation of water in the subsidence area. The hydrograph of test well 527 indicates the water level in the well is not immediately affected by surface pumping, but after January 1948 shows the effects of drainage of water downward through the expanding land subsidence areas. Test well 531 is distant from both the immediate effects of surface pumping and those of land subsidence. It is probable that the water level in each of these test wells was at, or above, an altitude of 1,510 feet before any type of drainage began.

The water level in test well 503 declined more than 70 feet from July 1937 to July 1942. From the latter date until the summer of 1951 the water level declined, at a reduced rate, about 25 feet more. The reduction in the rate of lowering was caused both by the decreased yield of the wells pumping from the overburden and by the fact that the rate of pumping from the workings, which was relatively constant, reflected a higher rate of capture of what would have been rejected recharge from precipitation if no drainage had been taking place, and, hence, a reduction in the rate of removal of water from storage. In the period 1941 to 1951, numerous small rises of several feet in the water level occurred during the summer months caused by the recharge from precipitation. A comparison of the hydrograph of well 503 with the rate of pumping both from the overburden and from the mine indicates that the water level in the well declines when the rate of pumping from either place increases.

Although test well 527 was drilled four years later than test well 503, and the altitudes of the water level in both wells were approximately the same in 1941, it is possible that a large decline in water level occurred at the site of well 527 -- similar to that which occurred in 503 prior to 1941. The water level in test well 527 declined very slowly from the time the well was drilled until the end of 1947. This decline was probably caused by the outward expansion of the cone of pumping depression, and the decreased rate of decline was caused by the decreased yield of the wells in the overburden. However, beginning in 1948, the water level declined at a more rapid rate through 1950. Comparison of the hydrograph of this well with the rate of pumping from the mine shows that, as the average rate of pumping increased about 270 gpm, the water level in this well declined. Since there were no increases in the rate of pumping from the overburden, it is apparent that an additional subsidence area in the vicinity of test well 527 must have permitted the greater percolation of water downward into the mine, thus causing additional drawdown at the well. The hydrograph of this well also shows minor rises in the summer and autumn of each year due to recharge from the melting snow cover of the preceding spring.

Test well 531 is approximately 3,000 feet west of the zone of subsidence and the main area of surface pumping at the mine. The hydrograph of this well does not show the rapid decline in water level caused by the development of the cone of depression originally as the effects of decreased withdrawals at a later date masks the earlier effects owing to the time lag and the distance from the center of pumping. This hydrograph shows the effects of recharge from the melted snow cover.

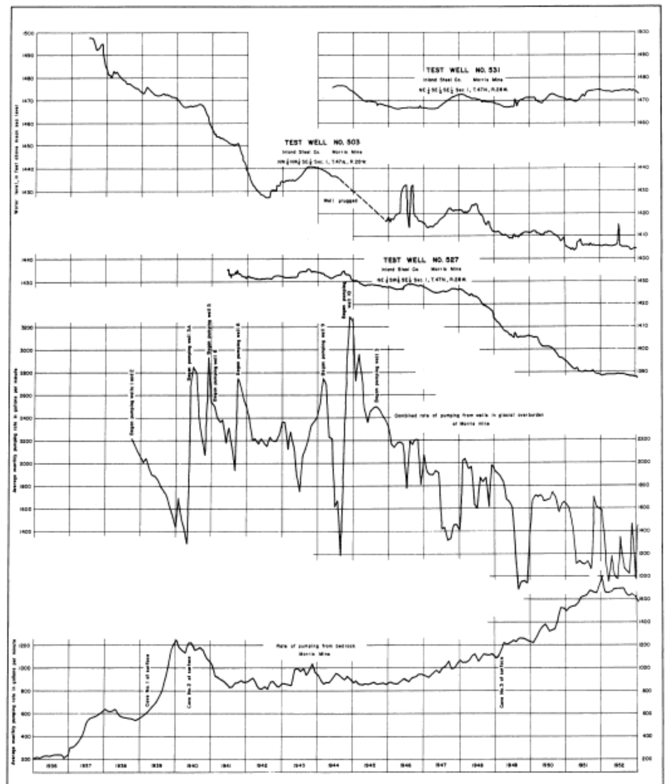

FIGURE 6. GRAPHS SHOWING FLUCTUATIONS OF WATER LEVELS AND RATES OF PUMPING IN THE VICINITY OF THE MORRIS MINE MARQUETTE DISTRICT, MICH.

Figure 6. Graphs showing fluctuations of water levels and rates of pumping in the vicinity of the Morris Mine, Marquette District, Mich.

Maas and Negaunee Mines Area

Maas mine test well 1-W is south of the shaft and on the northwest side of the subsidence area. The hydrograph of this well (see fig. 7) reveals a rapid decline of the water level during 1940 and 1941, immediately after pumping from the overburden began. The hydrograph shows fluctuations of the water level from 1942 through 1948, part of which were caused by discontinuous operation of the surface wells and part by recharge. Correlation of the water level in this well with the rate of pumping from the mine indicates that the increased rate of pumping is not accompanied by an increased lowering of the water level in the test well. Additional information obtained in 1953 indicated no increase in the rate of pumping from the mine when a nearby surface well ceased pumping. This may be interpreted that the test well is not within the cone of influence of the pumping from the mine, a condition which is contrary to the evidence shown by contours of the water level on figure 5. A possible explanation of the condition is that the point of inflow to the mine is between the test well and the source of recharge, and the water level in the well represents the condition of excess flow past the point of inflow to the mine. This explanation satisfies the condition in the correlation that the water level in the test well is high when the rate of pumping from the mine is at a peak. Further deductions on this basis would indicate that pumping from the overburden in the vicinity of the test well would not diminish the inflow to the mine greatly. To reduce the inflow to the mine the pumping of the overburden would have to be located up the ground-water gradient from the point of inflow to the mine. Information as to the location of the point of inflow is lacking, but a possible site would be west of the probable fault in the bedrock which is near the bottom of the northeast-trending buried valley under the city of Negaunee in sec. 6, T. 47 N., R. 26 W.

Another possible explanation for the conditions observed at this test well is that the point of inflow to the mine is at the east end of the cone of influence shown on figure 5. At this distance the effects of the increased rate of pumping are masked by other hydrologic conditions within the cone. However, this location for the point of inflow does not fit the development of the cone as outlined by the contours of the water level.

Negaunee mine test well 7 is northeast of the subsidence area between the Maas and Negaunee mines and is within the cone of depression of the well unwatering the overburden on the Negaunee mine property. The hydrograph of this well indicates a direct relationship between water levels in the overburden and the pumpage from bedrock in the Negaunee mine. Thus when water levels were highest, more water was pumped. The effectiveness of surface pumping in the Negaunee mine area is discussed later, in the section on the history of control of water.

Athens Mine Area

Athens mine test well 104W is due south of the subsidence area of the Athens mine, in Partridge Creek valley. The overburden in this area is approximately 55 feet thick and is composed of permeable materials which allow considerable opportunity for downward percolation of water from the land surface to the bedrock valley. Two wells were constructed to unwater the overburden in this area, but the yields were small because the saturated thickness was small. A comparison of the hydrograph of test well 104W with the pumpage from the bedrock at the Athens mine indicates that the higher the ground-water levels the greater the pumpage. Examination of the contour map of the bedrock surface (fig. 3) reveals that the Athens subsidence area is in the lowest part of the bedrock valley and tends to drain most of the valley fill.

Mather A shaft area

Test well Mather A-32 was drilled in the summer of 1947, prior to the installation of a well for unwatering the overburden in that area. The hydrograph of this test well shows both a decline caused by pumping from the surface well and several small rises caused by recharge from precipitation falling in that drainage basin. The hydrograph of this well (fig. 7) reveals no correlation with the rate of pumping from the mine, and since there is no evidence of subsidence it is probable that the downward percolation of ground water from the overburden is restricted.

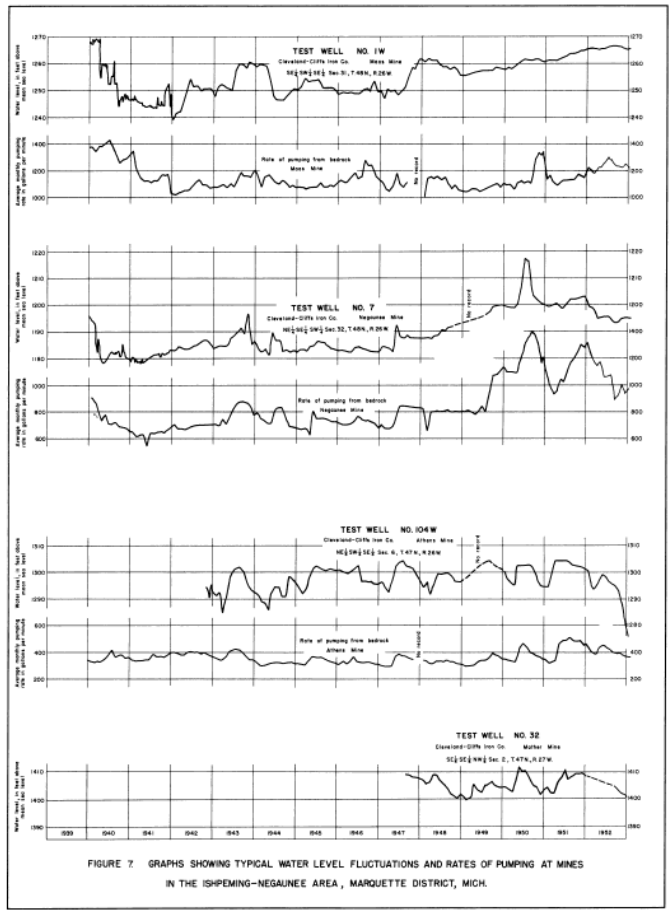

Figure 7. Graphs showing typical water level fluctuations and rates of pumping at mines in the Ishpeming-Negaunee area, Marquette District, Mich.

Recharge

Recharge is the addition of water to the ground-water reservoir. The water may be derived either from precipitation falling in the form of rain or snow, or it may result from induced downward percolation from the surface water in those areas where the water table is below the surface-water level and where geologic conditions are favorable for such a movement to take place. Of the total precipitation falling on the district, some is discharged by direct surface runoff, some percolates downward to recharge the ground-water reservoir, arid the remainder is discharged by evaporation and transpiration. Only a fraction of the precipitation, therefore, enters the interstices of the soil and of this only a portion reaches the water table. Only when the amount of water absorbed by the soil is greater than that which can be held against the force of gravity does the excess water move downward to the water table.

Recharge from Precipitation

In the Marquette district the greatest ground-water recharge is generally received from the accumulated snow cover which melts during the spring months. At this time the vegetal cover is usually dormant although beginning to come to life. Where there are permeable materials at the land surface, the water percolates downward, perhaps being deflected laterally by poorly permeable materials, until it reaches the water table. The location of the different types of glacial deposits at the land surface is shown in figure 4.

The most permeable glacial deposit is the outwash, which is generally located in the topographic valleys. The least permeable materials are the tills and lacustrine deposits. The tills occupy the sides and margins of the valleys. Considerable surface gradient combined with a low permeability of the surface materials prevents a large amount of ground-water recharge in the periphery area; although, due to local sandy and gravelly conditions, the amount of recharge may range from a negligible amount to values of the same magnitude as those for outwash materials. Most of the wells in which the fluctuations of the water table are recorded are located in the outwash plains, as these materials lend themselves more readily to the development of ground water, and consequently these locations are the only points available for quantitative studies of recharge.

Detailed correlation of the rises in the water table with precipitation in the past 10 years indicates that, if an effective porosity or coefficient of storage of 0.20 is assumed, an average of 28 percent of the precipitation falling on the outwash plains reaches the ground-water reservoir as recharge. In a buried valley where the recharge percolating down the buried bedrock hillside is added to that percolating in a vertical direction through the glacial materials, the total accretion to the reservoir, as measured in the wells in the buried valley, indicates an amount considerably above that which would normally be expected, depending on the ratio of valley areas to hillside areas. In the Morris mine area near North Lake the average recharge is equivalent to about 46 percent of the annual precipitation, in the area east of Negaunee at the Maas and Athens mines the effective recharge is about 36 percent; and in the valley northeast of Ishpeming near the Mather mine the recharge is about 32 percent. It is believed that an average value for the district would be between 20 and 25 percent of the normal precipitation, considering all the types of surface materials.

Recharge from Surface Water

In order that the reader may better understand the movement of water by percolation from a surface-water body to the ground-water reservoir, this discussion is prefaced by an explanation of the factors involved. In order to have vertical percolation three hydraulic conditions must exist, namely, (1) The stream bed must be permeable enough to allow the downward leakage, (2) the materials below the stream bed must be sufficiently permeable to accept the leakage, and (3) the head in the materials below must be below that of the water in the stream. If any of these conditions is not fulfilled or provides a limiting factor, the leakage from the stream will not occur or will be limited, furthermore, the quantity of percolation is controlled both by the minimum value of permeability of either the stream bed or the material below and by the hydraulic gradient between the stream and the deposit. Permeability is a function of the number, size, and interconnection of the openings within the wetted perimeter of area under consideration, and its value may range from a small to a large number. Usually the gradient does not change greatly in a short period of time.

Thus it can be shown that seepage losses by downward percolation are functions of the wetted perimeter of the stream channel rather than the quantity of water flowing in the stream. For this reason. in a given stream the losses are rather constant for short periods of time.

Recharge to the ground-water reservoir from water flowing on the land surface has been investigated, by means of gain-and-loss measurements on sections of the rivers and ditches, percolation studies, and correlation of these flows with the fluctuations of the ground-water levels.

<u>Seepage Investigation of Flow of the Carp River near North Lake</u>

In order to investigate the relation of flow in the Carp River near North Lake to the ground-water reservoir, measurements of flow were made at intervals along the channel during the periods of low flow in 1948 and 1949. Field reconnaissance on April 25, 1949 of North Lake, which is a source of the Carp River, indicated that the lake was spring fed. Springs in the swamp area west of the lake, measured and estimated, showed a total surface inflow to the lake of 365 gpm on this date. On the same date the measured outflow of the lake was 632 gpm. East of the lake the Carp River flows on an outwash plain and over a zone where the ground-water level has been lowered about 70 feet by surface pumping and by mine operations. Measurements of the flow in this section in the winter and spring of 1949 indicate the Carp River loses water at a uniform rate by downward percolation. Measurements on January 10, and March 30, 1949, when the outflow of the lake was 302 and 329 gpm respectively, showed no flow in the channel 3,000 feet downstream. Measurements on April 15, April 25, and June 29, 1949, when the outflow was 1,111, 632, and 428 gpm respectively, showed flows of 637, 182, and 159 gpm at a distance of 4,300 feet downstream from the outlet of the lake. These measurements suggest a rate of loss in the order of 0.1 gpm per linear foot of channel or about 15 gallons a day per square foot of wetted channel bottom. These rates are normal percolation rates for this type of material, but if the channel bottom were covered with clay or less permeable materials, other factors being equal, the rate of percolation would be less.

An investigation of the relation of the flow of water through the ditch which diverts the Carp River north to Goldmine Greek was made in 1948 by miscellaneous measurements and by gaging the flow above and below the Morris mine settling pond. In September 1948, before the settling pond was in operation, the measurements indicated a gain in the ditch from ground-water seepage at an average rate of 5 to 40 gpm. After the settling pond was filled, the sum of the pumpage into the pond and the inflow at the upper gaging station exceeded the outflow at the lower gaging station by about 350 gpm. Evaporation, (Records of evaporation at Germfask, Mich., U. S. Weather Bureau, Climatological Data, Michigan, estimated to be 25 inches per year for the 6 months of free water surface, could average approximately 10 gpm. The difference, 350 minus 10 gpm plus the normal gain from ground water seepage of 5 to 40 gpm, probably recharges the ground-water reservoir. Table 11 summarizes the flow at the lower gaging station on the Carp River diversion ditch.

Seepage Investigation of Flow of the Carp River below Morris Mine

A seepage investigation of the reach of the Carp River from Morris mine southward to the bridge on U. S. Highway 41 indicates the bed of the river has been fairly well sealed with a deposit of iron-bearing sludge deposited by water pumped from the mine. However, as the mine water is now diverted to the settling pond, only 317 gpm was measured in the channel near the mine and 312 gpm about 1,650 feet downstream on May 17, 1949. Clear water from the surface wells on the Morris mine property is discharged into the channel below the second measuring point. From this point to the bridge at U. S. Highway 41, a distance of about 3,000 feet, measurements indicate a loss of 100 gpm. In this latter reach the river flows on an outwash plain and along a boulder sluiceway in which conditions are favorable for a large percolation loss if the water table lies well below the stream surface. However, in the lower part of the reach the water table is at or near the same level as the stream surface. Although these measurements indicate that the seepage losses in the Carp River below the Morris mine are small, these losses could be much larger when the stream flow is greater and occupies a larger channel.

Other surface flows in the vicinity of North Lake were investigated for their ability to recharge the ground-water reservoir. Little Goldmine Creek (NW¼ sec. 1, T. 47 N., R. 28 W.), which enters the Carp River diversion ditch, was found to lose more than 400 gpm between the Chicago & North Western Railway Co. bridge and its outlet at the ditch, in the spring of 1949. Likewise, the stream heading in sec. 34, T. 48 N., R. 28 W. and flowing southward past the Barnes-Hecker mine shaft loses its entire flow in dry periods in the reach between the shaft and the Barnes-Hecker drainage ditch. In the southern part of sec. 1, T. 47 E., R. 28 W. the low flow of the stream has been measured and estimated to be in excess of 300 gpm.

The determination of seepage losses, as described above, by miscellaneous current meter measurements is subject to changes in channel storage, changes in rate of flow. and errors in gaging. In these studies changes in both channel storage and rate of flow were neglected, as the flow at the lower point was so small generally that changes from these causes would only be a small part of the seepage loss. The errors in gaging the amount of water probably average about 5 percent of the flow for streams of this magnitude, while smaller streams may have errors of gaging as high as 10 percent and for larger streams the error may be as low as 2 percent. When seepage losses are determined from continuous flow records at specially constructed sites the above errors are reduced to a very small percentage.

Seepage Investigation of flow of Partridge Creek at Negaunee, Mich.

Study of the gains and losses of Partridge Greek as it passes around the subsidence area south of the Athens mine was made by obtaining the difference in flow above and below the area. At the upper measurement site a modified Parshall flume with a 2-foot throat was installed downstream from the culvert where the creek passes under the tracks of the Chicago & North Western Railway Co, about one-eighth of a mile north of the S¼ cor. sec. 6, T, 47 N., R. 26 W. A similar installation was made downstream from the culvert at the Lake Superior & Ishpeming Railroad overpass about 700 feet north of the SE cor. sec. 6, T. 47 N., R. 26 W. A water-level recorder obtained continuous records of the stage and consequently the flow at each flume at both sites from August through November 1948 and from April until July 25, 1949 when the upper flume was destroyed by a flood. The study indicated the losses ranged from a maximum of 40 gpm in April 1949 to a minimum of 14 gpm in October 19489 and averaged about 25 gpm for the 7-month period of record. A condensed table of the record of flow for the lower measuring site is shown in table 13.

In August 1952, when the rate of pumping at the Athens mine increased considerably a new flume was installed above the subsidence area. Continuous records of the flow above and below the subsidence area were obtained during September and October and it was determined that the losses averaged about 150 gpm in the reach. In this same reach where previously the losses had been small, it was apparent that the subsidence had extended upward to the stream bed and permitted an increased downward percolation of water. The first indication of the outward expansion of the subsidence zone was noted when the water level in an observation well about 20 feet north of the stream channel suddenly declined from slightly above the bedrock surface to about 30 feet below it during March 1952. This cracking of the bedrock surface drained the water from the materials filling the bedrock valley, but the subsidence did not extend upward to the land surface until several months later. A steel flume over

2,000 feet long was installed in the creek bed to eliminate the seepage losses in this reach.

<u>Seepage Investigation of flow in the Cambria-Jackson Mine Ditch</u>

A study of the flow in the ditch containing the mine»water discharge from the Cambria-Jackson mine was made in October and November 1949 to determine if there was a recirculation of the water in the ditch where it passes over a fractured bedrock zone near the surface subsidence area. Two 18-inch sharp-crested, free flowing rectangular weirs were constructed -- one above and one below the critical reach -- and recording gages giving the continuous record of the head of water over the weirs were installed at each site. The daily losses ranged from 31 to 6 gpm and averaged 18 gpm for 17 days of operation. The losses were less than 2 percent of the total flow.

<u>Stream runoff in the district</u>

The Carp River near North Lake, Partridge Creek at Ishpeming, and Partridge Creek at Negaunee were gaged primarily to determine the recharge from streamflow in the vicinity of mining operations, and since no records of streamflow are available in the district these are included in tables 11, 12 9 and 13. The amount of runoff in the district for the years 1949 and 1950 can be estimated by comparison with the streamflow records in these tables. The principal factors in determining the runoff from precipitation are the duration and intensity of the rains, slope of the land surface, type of soil and subsoil. and types of vegetation. Hydrologic studies made on the river basins in the northern peninsula reveal that in an area where the annual precipitation is about 30 inches per year about 15 inches of runoff occurs as surface flow and 15 inches is discharged by evapotranspiration. Of the 15 inches occurring as runoff about 9 inches is direct surface or flood runoff and the remainder of 6 inches is base flow or ground-water runoff. The records shown in tables 11, 12, and 13 indicate that the runoff in the Marquette district constitutes a considerable proportion of the precipitation, although the period of record is too short to determine the ratio of direct runoff to base flow or ground-water runoff.

<u>General Discussion</u>

Recharge from the streams and ditches is small except in those areas where the streams arid ditches flow on pervious outwash and where the water table has been lowered below the surface-water level. Should mining developments take place in the Carp River valley west of Ishpeming in secs. 4, 9, and 17, T. 47 N., R. 27 W., it is very probable that considerable recharge would be induced from the river. In the lower reaches of the Carp River east of Negaunee in sec. 33, T. 48 N., R. 26 W., it is probable that considerable recharge could be induced to flow toward the mines as the water level has declined greatly in the vicinity of the mine subsidence west of this location. It is believed that the induced recharge is of minor amount at present. The water in the Maas and Negaunee mines is believed to be interception of the normal eastward ground-water flow through the buried valley rather than induced recharge from the river. Recharge to the bedrock through downward percolation in mine subsidence areas is being reduced to a minimum by diverting all the surface streams from the critical areas and reducing the saturated thickness of the overburden by pumping.

Recharge to the Bedrock through Mine-Subsidence Areas

In those areas where mining has broken the bedrock and caused subsidence at the land surface a large part of the precipitation easily recharges the ground-water reservoir. Slumping at the land surface produces a depression which diverts all surface drainage to the area. The broken condition of the bedrock roof of the mine, with the system of explorations, drifts^ and stopes below, provides passageways for transmitting the water to adjacent mined areas. Those mines where the broken bedrock surface is above the "shoreline" of the ground-water reservoir pump less of this direct recharge, as only the precipitation on the intermediate area percolates to the mine workings. Examination of the hydrographs of pumpage from the Cambria-Jackson and Lloyd mines, where the bedrock is broken above the shoreline of the ground-water reservoir, indicates that the peak pumpage rate is less than a hundred gallons a minute greater during periods of recharge from snow melt than the average rate of pumping for the remainder of the year.

Where the subsidence areas are located below the ground-water .shoreline. the bedrock is recharged continuously from the saturated overburden. Hydrographs of the pumpage in those mines where the bedrock is broken below the water table indicate a general high rate of pumping with a peak pumping rate about 100 gpm greater during periods of direct recharge than the average rate for the remainder of the year. At the Athens, Blueberry, Maas, Morris, and Negaunee mines the bedrock is broken below the water table.

An unusual condition exists at the Morris mine subsidence area where the overburden materials filling the caved zone in the bedrock are poorly permeable and a perched water zone is found within the subsidence area. At this location the typical section of the subsurface materials consist of a basal till overlain by a thick unit of lacustrine material overlain by about 40 feet of sand and gravel. When the bedrock roof of the mine collapsed the poorly permeable till and lacustrine materials slumped into the opening, partially plugging it and thus preventing a rapid downward movement of water from the saturated overburden. The sands and gravels formerly near the land surface are now at and below the water table, and the saturated materials adjacent to the subsidence area transmit water to the slumped section so that a perched pond exists in the center. This perched pond or portion of the exposed water table is maintained because the rate of precipitation falling on the caved zone and the rate of contribution of water from the saturated wall materials of the cave exceed the vertical percolation rate through the poorly permeable plug filling the opening in the bedrock. It should not be deduced from the above statements that the mine workings below are relatively dry owing to this plugging, because the amount of water percolating downward around the edge of the slumped area and through the unplugged fractured bedrock is large.

Discharge

Ground-water discharge is the discharge directly from the zone of saturation or from the capillary fringe and may take place through evapotranspiration or as a hydraulic discharge through springs, seeps, wells, and mine pumping.

Discharge by Evapotranspiration

Evapotranspiration occurs where the water table is shallow and vegetation covers the land surface. Apparently considerable water is discharged by this method, as the recharge from the normal precipitation during the growing season is small. Since about 16 inches of precipitation occurs from May through September it might be deduced that the evapotranspiration use of water is about half the normal annual precipitation. This estimate agrees with the data on stream flow (p. 50). Although the discharge by this process is large, it is not important from a water control standpoint except as a factor in the hydrologic balance of water movement into and out of an area.

Discharge by Springs and Seeps

A relatively large amount of ground water is discharged through springs and seeps in the district. Areas where the ground water is at shallow depths are common along the surface streams. These areas are characterized by swamp-type vegetation and a boggy condition of the ground. Many of the small creeks and intermittent streams head in these seep areas. These areas are so prevalent that they are shown as swamp and lacustrine deposits on figure 4. Probably the most important spring zone, from the mine-drainage standpoint, is in secs. 1 and 2, T. 47 N., R. 28 W., near North Lake. It forms the headwaters of the Carp River, whose flow ranges from 200 gpm to several thousand gpm. Drainage programs probably have decreased the flow of springs in this area by diversion of ground water through wells and mine pumpage. It is probable that the drainage at the Maas and Negaunee mines has decreased the flow of the springs in the Carp River basin in secs. 32 and 33, T. 48 N., R. 26 W. In other parts of the district it is likely that many of the large spring zones have been similarly unwatered.

Discharge by Wells and Mine Pumping

Discharge from ground-water systems in the district is also brought about both by surface-well systems at some of the mines, and by unwatering bedrock formations during mining.

<u>History of Control of Water</u>

The first attempt to control water in the glacial overburden in the district was at the Morris mine, where wells were drilled and equipped with pumps to lower the head of water over the ore body. Pumping began in 19389 and the water level over the ore body was lowered to about 70 feet below land surface after 10 years of pumping. The number of wells was increased from two in 1938 to 10 in 1944 and the withdrawals have increased progressively, averaging slightly more than 2,000 gpm for the entire period of pumping. The water pumped from the bedrock has increased from an average of 235 gpm in 1936 to an average of 1,340 gpm in 1950. The increase in the mine pumpage has been due to the fact that the bedrock roof above the mining operations collapsed in 1939, affording greater opportunity for the downward movement of water.

Shortly after the overburden-drainage program was started at the Morris mine, two drainage drifts were constructed in the bedrock near the ledge surface at the Blueberry mine -- one to unwater the overburden and thus prevent water from entering subsidence areas, and the other to decrease the flow of water entering the mine in the vicinity of the shaft. Both drifts were located very close to, but below, depressions in the bedrock surface where considerable water was percolating downward into the mine. The drifts are only a few hundred feet long, and vertical holes were bored from the land surface downward to tap them. Each hole was cased and equipped with a well screen to allow drainage of water into the drainage drift. The drift south of the mine shaft yields more than 100 gpm from four of these inverted wells. The drift southwest of the mine shaft, which is under a separate bedrock depression, yields an excess of 200 gpm from four similar inverted wells. Measurements of the decline of the water table in the vicinity of these drifts indicate that the retreating "shore-line" of the ground-water reservoir "uncovered" or unwatered those bedrock areas where the water was percolating into the mine workings. These interceptor drifts were reported to be successful in controlling the water, in that by concentrating the water in one place it was more economical to lift the water a few hundred feet than to have the same amount of water dispersed in the mine at greater depth, thereby necessitating greater collecting and lifting costs.

In the Negaunee area surface pumping of the overburden began at the Maas, Negaunee, and Athens mines in 1940. Large-yield wells could not be developed in these areas so that a total of only 1,000 gpm was pumped at the Maas and Negaunee mines from four wells, and about 60 gpm was pumped at the Athens mine. A correlation of the water levels in the glacial overburden with the water pumped from the Maas mine indicates that pumping the surface wells did not decrease the quantity of water in the mine workings. Pumping of the well at the Negaunee mine at the rate of 400 gpm is reported to have decreased the flow of water from the ninth level of the mine from about 638 gpm when the pump was started to about 353 gpm 8 months later. The flow on the ninth level continued to decrease after this period, and it is believed that the reduction, in a large part, was due to the unwatering of the overburden by the pumping of this well. In the vicinity of the Athens mine pumping from the overburden by wells whose individual yields range from 15 to 30 gpm probably decreases the quantity of water percolating into the mine by an equal amount, as these wells are located very close to the subsidence area. It is believed that all the water in the buried bedrock channel in the Athens mine area eventually seeps into subsidence cracks and passes downward into the mine workings. A pump in the Breitung-Hematite shaft south of the Athens mine maintains a water level considerably below the bedrock surface, and the records of the amount of water pumped from the Athens mine beginning in 1920 indicates that when the Breitung pump was in operation considerably less water was pumped from the Athens mine.

Table 14 shows the estimated rate of withdrawal of ground water per year from the overburden and bedrock for the past 22 years. The total rate of pumping has been increasing; however, it is slightly influenced, with a lag of a year, by the cycles of precipitation. The increased pumping rate below ledge is due to the expansion of mining operations and the spread of subsidence. The pumping rate above ledge has decreased because of the reduction in the saturated thickness of the material transmitting water to the wells and the general decrease of the well efficiencies.

The estimated pumpage figures used in this report are based on data obtained from various sources. The mine pumpage data was obtained from the pump operators, records and the records compiled by the engineering staffs of the companies. It is believed that the totals are essentially correct even though the underground pumpage figures may be slightly high because the records may have been computed on the basis of pump efficiencies that were higher when the pumps were installed than they were after some use.

Year	Pumpage above ledge	Pumpage below ledge	Total by year
1930	---	4,690	4,690
1931	---	4,178	4,178
1932	---	4,345	4,345
1933	--	4,002	4,002
1934	---	4,002	4,002
1935	---	4,166	4,166
1936	---	4,394	4,394
1937	---	4,682	4,682
1938	711	5,091	5,802
1939	1,785	5,272	7,057
1940	3,693	5,351	9,044
1941	3,976	4,751	8,727
1942	3,911	4,645	8,556
1943	4,124	5,077	9,201
1944	3,751	5,052	8,803
1945	3,540	5,094	8,634
1946	3,017	5,001	8,018
1947	2,540	5,351	7,891
1948	2,728	5,156	7,884
1949	2,256	5,512	7,768
1950	2,399	6,510	8,909
1951	2,142	7,113	9,255
1952	1,903	7,058	8,947

Table 14. Estimated average annual pumpage in Marquette Iron-Mining district (gpm).

Movement of Ground Water

General Flow Conditions in Overburden

Movement of ground water in the permeable water-bearing formations involves (1) a surface zone of flow where gravitational influences govern the migration, and (2) a deep zone of flow where the formations may be considered as having definite upper and lower boundaries and the flow is through well-defined conduits of permeable materials.

In the upper zone of circulation in the district, or where water-table conditions prevail, the motion of ground water conforms primarily to the controls exercised by the slopes and grades of the land surface. Actual determinations show that the water table has a slope less steep than that of the land surface, but the surface divide or watershed usually coincides with the line of ground-water divide and the motion of the ground water is along lines similar to the lines of drainage followed by the surface drainage. In the buried bedrock valleys of the district the actual lines of ground-water movement are down slope at right angles to the contours of the water level as indicated on figure 5.

The similarity of the surface and ground-water gradients is common. The horizontal distribution and motion of ground water is influenced first of all by the form of the first effectively impervious layer encountered below the water table. For example, the outcrop of an impervious stratum may force the ground water to the land surface or it may divert or concentrate the flow into a strong current through the remaining opening. Movement of the ground water through the buried valleys of the district follows well-defined laws of laminar flow.

The movement of ground water in the upper zone of circulation is caused by the differences in hydrostatic head in the different parts of the strata. The relation among the various factors governing the quantity of flow in permeable water-bearing formations is best expressed by a variant of Darcy's law which may be stated mathematically as follows:

$$Q = T\,I\,W$$

Where Q = flow in gallons a day through a strip of the water-bearing formation W feet wide with a depth equal to the saturated thickness of the formation.

T = coefficient of transmissibility in gallons per day per foot of width of saturated formation, under a hydraulic gradient of unity.

I = hydraulic gradient in feet per foot along slope of formation in the direction of flow.

W = width of the water-bearing formation in feet, perpendicular to the direction of flow.

The value of the factor T or transmissibility in the above modification of the formula expressing Darcy's law is governed by the thickness and physical properties of the water-bearing formation, particularly the size-variation and packing of the individual particles making up the formation. These physical factors determine the frictional resistances to the flow of ground water.

Darcy's law applies approximately to the bedrock formations where the water moves through the fracture and vug systems, provided these openings are small in comparison to the width and depth of the formation and the velocity of movement is low. It may be applied to dipping formations by expressing the gradient as the difference in altitudes of the points of measurement, such as open mine workings, divided by the length of the formation between these points.

Ground-water movement in the saturated overburden around any system of artificial withdrawal, such as mining operations or unwatering devices, follows Darcy's law, but for quantitative studies certain formulas provide a better understanding of the relation among the physical characteristics of the water-yielding formation, the time, and the quantity of water withdrawn.

The withdrawal of water from any water-yielding formation causes the water levels to decline in the vicinity of the point of withdrawal, and the water table or piezometric surface around the point of withdrawal assumes an approximate shape of an inverted cone with the apex of the cone at the point of withdrawal. For a well, open pit. trench or infiltration gallery the shape of the cone is modified or elongated to correspond with the shape of the unwatering structure, in that the water flows radially or laterally by the easiest path to the structure. However, the over-all size, shape, and rate of growth of the cone of depression created by the drainage structure are dependent on the rate and duration of the drainage, the transmissibility and storage coefficients of the material, the increase, if any, in recharge induced by the declining water levels, the natural discharge that is captured, and the hydrogeologic boundaries of the formation. The lowering of the water level is dependent on the variables mentioned above and the distance from the point of withdrawal.

In order to express a general equation for relation among the variables that govern the magnitude of the unwatering effects certain basic assumptions are made. It is assumed that the formation is constant in thickness, infinite in areal extent, and homogeneous and isotropic (transmits water with equal facilities in all directions). It is assumed further that the water may enter the unwatering structure from the full thickness of the formation.

Flow conditions near a circular opening in the overburden.

The relation among the hydraulic properties of the formation, the rate and duration of pumping, and the change in water level caused by the withdrawal of water from a circular opening in a formation is expressed in the following formula developed by Theis (1935, pp. 519-524):

$$s = \frac{114.6Q}{T} \int_{\frac{1.87r^2S}{Tt}}^{\infty} \frac{e^{-u}du}{u} \qquad (1)$$

Where s = drawdown, in feet, at any observation point in the vicinity of the circular opening from which water is withdrawn at a uniform rate.

Q = rate of withdrawal of water, in gallons per minute.

T = coefficient of transmissibility, in gpd/ft.

r = the distance in feet, from the point of withdrawal to the point of observation.

S = coefficient of storage, a dimensionless decimal fraction.

t = time, in days, since the withdrawal of water began.

The above formula is generally applied to the withdrawal of water from the formations through the use of vertical wells, but it can be applied also to any circular opening of a large radius such as an open pit penetrating the whole formation or circular zone of subsidence where the water is withdrawn from the bedrock below.

<u>Flow conditions near a linear opening in the overburden</u>

In order to express the relations among the hydraulic properties of the formation, the rate and duration of withdrawal of water, and the change in water level caused by pumping from a long open trench or infiltration gallery, Theis (Stuart and others, 1948, pp. 46-47) developed the following formula:

$$s = \frac{Qr}{2T}\left[\frac{e^{-z^2}}{\sqrt{\pi}\, z} - 1 + \frac{2}{\sqrt{\pi}}\int_0^z e^{-z^2}dz\right] \qquad (2)$$

where s = drawdown, in feet, at distance r and time t.

Q = quantity discharged from trench, in gpd per foot of trench.

r = distance of point of observation from the trench, in feet.

t = time since discharge started, in days

T = coefficient of transmissibility, in gpd/ft.

S = coefficient of storage, a dimensionless decimal fraction.

To determine the effectiveness of any drainage structure it is necessary to know the water-bearing characteristics of the formation. These may be determined by laboratory means, but the use of the disturbed and washed samples obtained during the drilling of test holes, or cores that may not be representative of the whole formation, somewhat invalidates the reliability of such coefficients; and more accurate values from undisturbed materials can be obtained by means of pumping tests. A pumping test is made by observing the drawdown or recovery of the water levels during and after pumping a well. By analysis of these data, values for the transmissibility and storage coefficient can be obtained. In other words, a pumping test is a means of determining, in a relatively short time, the equation (nonequilibrium formula with proper coefficients), that is, the mathematical expression for the profile of the cone of depression, in order that it can be used to predict the behavior of the water levels for longer times and for greater distances than are covered by the actual observations.

Methods of determining transmissibility and storage

In the Marquette district values for coefficients of transmissibility and storage have been obtained by the methods of Theis (1935, pp. 519-524) and Cooper and Jacob (1946, pp. 526-534) as applied to pumped wells. In the method of Theis the exponential integral of formula 1 is replaced by the term W(u) which is read "Well function of u" and the equation is rewritten as follows:

$$s = \frac{114.6\ Q}{T} W(u) \quad \ldots \quad (1\text{-a})$$

The value of the integral is given by the following series:

$$W(u) = \left(-0.577216 - \log_e u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} \ldots\right) \quad \ldots \quad (1\text{-b})$$

in which $u = \frac{1.87r^2S}{Tt}$ ..... (1-c)

Calculations of W(u) for values of u between 9.9 and. 1.0 x 10^{-15} are given by Wenzel (1942, facing p. 89). The "Well function of u" is plotted versus u on log paper to form a type curve for determining the transmissibility and the storage coefficient of the formation tested. The observed drawdowns are plotted versus r^2/t on similar log paper. The graph of the observed data is matched with the type curve by superposition, keeping the axes of the two graphs parallel, and values of r^2/t, s, W(u), and u are selected at any convenient match point. The value of transmissibility is obtained by substitution of the match values in equation 1-a, and the value of the storage coefficient is then obtained by substitution in equation 1-c.

A more convenient nonequilibrium solution for transmissibility and storage coefficient is described by Cooper and Jacob (1946. pp. 526-534). For small values of u (small r or large t), W(u) given by equation 1-c is approximately,

$$W(u) = -0.577216 - \log_e u \quad \ldots \quad (1\text{-d})$$

and $$s = \frac{114.6\ Q}{T}\left(\log_e \frac{Tt}{1.87r^2S} - 0.577216\right) \quad \ldots \quad (1\text{-e})$$

The value of r is constant at a given observation well., and equation (1-e) may be written

$$s_2 - s_1 = \frac{114.6\ Q}{T}\left(\log_e \frac{Tt_2}{1.87r^2S} - \log_e \frac{Tt_1}{1.87r^2S}\right)$$

$$= \frac{114.6\ Q}{T} \log_e \frac{t_2}{t_1} = \frac{263.5\ Q}{T} \log_{10} \frac{t_2}{t_1} \quad \ldots \quad (1\text{-f})$$

where s_2 and s_1 are drawdowns observed at times t_2 and t_1 respectively. Drawdown is plotted versus the log of t on semilog paper, producing a straight-line graph. If an interval of one logarithmic cycle is selected from the time-drawdown graph of the observations made in any observation well near the pumped well, the value of transmissibility can be obtained from the following equation:

$$T = \frac{263.5\ Q}{s_2 - s_1} \quad \ldots \quad (1\text{-g})$$

where s_2-s_1 is the difference in drawdowns through one log cycle. The storage coefficient is obtained from equation (1-h).

$$S = \frac{0.301\ Tt_o}{r^2} \quad \ldots \quad (1\text{-h})$$

where to is the time where the drawdown is zero on the graph. To determine to the plotting of equation (1-f) is used and the line representing s versus t is extended to s = 0 and this value of time is substituted in equation (1-h) for the determination of the coefficient of storage. The value of T has been determined in equation (1-g) and r is the distance, in feet, from the pumped well to the point of observation.

Both methods of solving the nonequilibrium formula (log and semilog plots) were used in analyzing pumping-test data for the Marquette district, as each has advantages not possessed by the other.

Table 15 shows the values of the coefficients of transmissibility and storage obtained by means of pumping tests on wells in the glacial overburden in the district. A considerable range in values was obtained and was to be expected owing to the nonuniformity of the materials being tested, and the low values for the transmissibility confirm the geological observations made on the subsurface materials that their water-yielding properties would be poor. The average transmissibility from the four areas in the district (11,000 gpd/ft) is very small when compared to the values obtained for equal saturated thickness of glacial materials in southern Michigan and other areas.

The range in transmissibility may be explained in part by the vertical discontinuity of materials. In the Morris mine area, where the coarse and more permeable materials are at or near the water table, and the finer materials are at depth, a rise in the water level of a few feet may cause a large increase in the coefficient of transmissibility. In this area the more permeable materials near the top of the glacial overburden have been unwatered after more than 10 years of drainage and the transmissibilities as shown in table 15 are those for a columnar section of as much as 100 feet of poorly permeable materials (classified locally as hardpan) with its associated thin stringers of sand and fine gravel. In wells 1 to 9 inclusive the formation probably yields water mostly through the thin stringers of sand and gravel in the hardpan, and their total thickness greatly affects the transmissibility of the formation in the vicinity of these wells. Well 10 penetrates an area of coarser materials that have not been completely unwatered to the top of the hardpan. The low transmissibilities at West Ishpeming, Mather mine area, and Humboldt are due both to small saturated thickness and to the poor sorting of the outwash materials yielding the water.

The computed coefficients of storage, reflecting the quantity of water drained from a unit volume, vary considerably with the duration of pumping -- probably due to the very slow drainage of water from the poorly sorted water-bearing materials. It also is probable that in certain cases the stratified arid lenticular sands and gravels function as artesian aquifers during short periods of pumping -- that is, the formation acts as a conduit and no actual unwatering of the formation takes place, but after prolonged unwatering takes place the coefficient of storage probably Increases greatly. The coefficients of storage computed from these tests range from a very small decimal fraction for short periods of pumping to values that approach the specific yield of the materials.

The effects of the hydrogeologic boundaries in pumping tests in the district were considered, where those effects were noted in the test results. In general the distance to the ledge “shore lines" (barrier boundaries) of the ground-water reservoir are known from examination and comparison of the bedrock-surface and water-level contour maps. In all the tests whose results are shown in table 15, the effects of barrier boundaries were noted. In some other tests, in which evidence of boundaries was questionable, the transmissibility also might be questionable, and such results were omitted from table 15. Where a recharge boundary (source of outside water added to system) was noted, the distance from the observation well was calculated by the method suggested by Ferris (1948, p. 1-12) and is shown in the table. Data from pumping tests show that a known barrier-type boundary increases the rate of lowering of the water level in the observation well, and a known recharge-type boundary decreases the rate of lowering. By the changes in the slope of the time-drawdown curve the type of hydrogeologic boundary can be determined.

In prediction of future water levels the effects of boundaries can be considered mathematically by the introduction of hypothetical image wells. In the case of a production well in a ledge valley, or in general, in the vicinity of a straight boundary beyond which no water can pass; the introduction of an image production well, located at an equal distance on the opposite side of the boundary and pumped at the same rate as the real production well, will simulate mathematically the effects of the boundary. In this case the drawdown produced within the cone of depression will be the mathematical sum of the actual drawdown of the production well plus the theoretical drawdown produced by the image production well at the point of consideration. Similarly where a production well is near a stream or line source of recharge and where the drawdown is negligible because of water being added to the hydraulic system as fast as it is being transmitted to the production well, the introduction of an image recharging well, located at an equal distance on the opposite side of the boundary and recharging the system at the same rate at which the real production well is pumped, will simulate the effects of the recharge boundary. In this case the drawdown at any point within the cone of depression will be the algebraic sum of the actual drawdown of the real production well plus the negative drawdown (build-up) produced by the recharging image well.

<u>Relation of water in overburden to flow in bedrock</u>

Water in mining operations can be considered a low-grade rock material that must be removed before the ore can be extracted. When the cost of controlling the water exceeds the margin of profit for the extraction of the ore. mining in a competitive market will cease. In the Iron River and Marquette districts water has been successfully controlled by diverting the water in the overburden before it reaches the mined areas. Considerable knowledge of the movement of ground water through the overburden is already available, but the principles which govern the flow into the mined bedrock, and consequently the extent to which the flow may be reduced by pumping from the overburden are not well defined. With this in mind, we shall develop the theoretical relationship between the saturated thickness of the overburden at the edge of a collapse area and the flow into the bedrock, with special emphasis on stabilized or equilibrium flow conditions. In each case the area of contact between the overburden and the bedrock, and the vertical permeability of the bedrock, are assumed to be sufficient to accept all the ground water the overburden is capable of transmitting. This assumption eliminates the possibility of a body of water being formed over the bedrock sink, since the existence of such a body would introduce an undesirable condition in that the flow into the bedrock then would be dependent on the height of water in the body above it. In this development the relationship between the saturated thickness at the edge of the bedrock zone and the capacity of the bedrock area only is being investigated.

CASE I, ONE DIMENSIONAL FLOW OF GROUND WATER OVER A PERMEABLE BEDROCK FLOOR

This simple form of flow condition assumes a long linear contact of a permeable bedrock under a saturated overburden (a broken collapse area in a bedrock valley) such that the ground-water movement through the overburden toward the bedrock contact is essentially linear. It is further assumed that "A" is the vertical permeability of the bedrock and is large enough to be. independent of the •head of the water over it.

In the section view given in figure 8, x_0 is the point at which the depth of water in the overburden is zero. In the following equations P is the permeability of the overburden, and "A" is vertical permeability of the bedrock. Considering a section of unit width, measured normal to the plane of figure 8, it is evident from Darcy's law, that the amount of water flowing through the overburden past the point x may be expressed as Py $^{dy}/_{dx}$. But this same amount of water percolates into the bedrock over the distance $x - x_0$ and can thus be expressed as $(x - x_0)A$. Equating the two expressions gives:

$$(x - x_o)A = Py\ dy/dx$$

Integrating to obtain the equation for the water-table profile,

$$\left(\frac{x^2}{2} - x\,x_o\right) = P/A\ y^2/2 + C$$

Evaluating C, where $x = x_0$, $y = 0$

$$C = -x_0^2/2$$

Substituting for C, and simplifying,

$$x - x_o = y\sqrt{P/A}$$

At points where x = L, y = H the equation becomes,

$$L - x_o = H\sqrt{P/A}$$

But the total quantity of water, Q, flowing into the area of contact with the permeable bedrock floor is equal to A(L - x_o) or, substituting the value for L - x given in the preceding equation,

$$Q = H\sqrt{AP}$$

Thus it appears that in the case where the permeable bedrock or linear broken area can accept all the water transmitted to it, that the amount of water flowing into the bedrock is directly proportional to the thickness of the water body at the edge of the broken area.

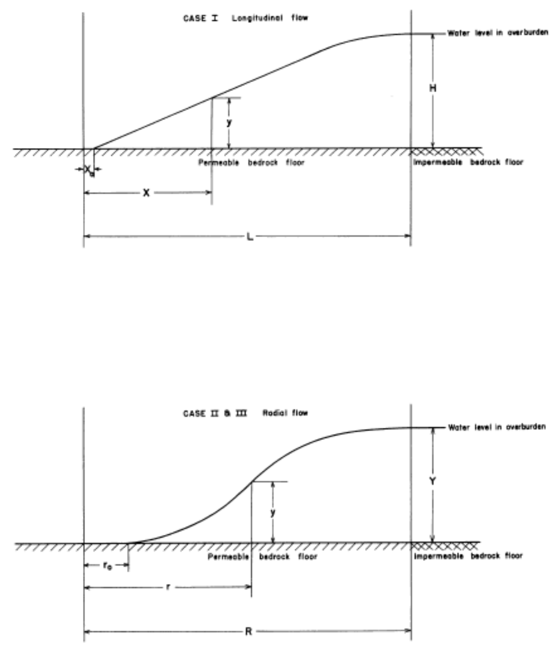

FIGURE 8. FLOW OF WATER INTO PERMEABLE BEDROCK FORMATIONS

Figure 8. Flow of water into permeable bedrock formations.

CASE II, MOVEMENT OF WATER INTO CIRCULAR PERMEABLE OR BROKEN AREAS IN BEDROCK

Having considered the relation of saturated thickness of the overburden to the flow into a porous bedrock floor where the flow in the overburden is essentially linear, we shall proceed to investigate the flow into a circular permeable or broken area where the flow pattern is radial.

In case II (fig. 8) we assume a homogeneous isotropic overburden of infinite areal extent to overlie an area of bedrock, circular in plan that is so shattered (due to mining operations) that water descends through random and many crevices as fast as it is made available by movement out of the overburden. Assume that the vertical permeability of the bedrock is large and equal to "A". Let "R" equal the radius of the shattered area and "Q" the amount of water coming into the area from the overburden. For case II assume that the overburden has a constant transmissibility "T" and that "T" does not diminish with the lowering of the water. This would be the condition found in nature where a thin gravel bed occurs under a clay or hardpan layer, and where the gravel is never unwatered. For this condition the transmissibility considered would be that for the gravel bed only, and the head or "saturated thickness" would be the distance from the piezometric surface to the base of the gravel bed.

Again considering a section as shown in figure 8, and equating expressions for the quantity of water moving laterally through a cylindrical shell of the overburden of radius r and the quantity Q, reduced by the flow into the bedrock over an annular area of width R - r, there results the relation:

$$Q - A\pi(R^2 - r^2) = 2\pi r\, T\, dy/dr$$

multiplying by dr/r,

$$Q\, dr/r - (\pi AR^2 - \pi Ar^2)\, dr/r = 2\pi T dy$$

integrating dy/dr,

$$Q \log_e r - \pi AR^2 \log_e r + \frac{\pi Ar^2}{2} = 2\pi Ty + C$$

$$(Q - \pi AR^2) \log_e r + \frac{\pi Ar^2}{2} = 2\pi Ty + C$$

evaluating G, $r = r_o$ where $y = o$

$$(Q - \pi AR^2) \log_e r_o + \frac{\pi A r_o^2}{2} = C$$

whence,

$$(Q - \pi AR^2) \log_e r/r_o + \frac{\pi A}{2}(r^2 - r_o^2) = 2\pi Ty \qquad (3)$$

Let $\pi AR^2 = K$, the quantity of water the broken area can absorb, when it is entirely covered by water. (The depth of water is assumed to have no effect.)

Let $Q = BK$, where $B<1$, inasmuch as the quantity K cannot be exceeded.

Then $\pi A(R^2 - r_o^2) = Q = BK$

$$r_o = \sqrt{K(1 - B)/\pi A}$$

$$R = \sqrt{K/\pi A}$$

Using these latter three relations and substituting appropriately in equation (3), as it is rewritten for points where r = R and y = Y, there follows:

$$(BK - K) \log_e \sqrt{\frac{K/\pi A}{K(1 - B)/\pi A}} + \frac{BK}{2} = 2\pi TY$$

$$\frac{K}{2}[(1 - B) \log_e (1 - B) + B] = 2\pi TY$$

$$Y = \frac{K}{4\pi T}[2.3(1 - B) \log_{10}(1 - B) + B]$$

substituting, πAR^2 for K

$$Y = \frac{AR^2}{4T}[2.3(1 - B) \log_{10}(1 - B) + B]$$

or

$$Y\left(\frac{4T}{AR^2}\right) = [2.3(1 - B) \log_{10}(1 - B) + B]$$

Constant transmissibility	
B	$Y\left(\frac{4T}{AR^2}\right)$
1.0	1.0
.9	.670
.8	.478
.7	.339
.6	.234
.5	.154
.4	.094
.3	.051
.2	.022
.1	.003
0	0

Table 16. Relationship of capacity "B" of circular permeable bedrock area to accept water, to saturated thickness "Y" of adjacent overburden. Case II.

Under these assumptions the flow decreases much more slowly than the decrease in saturated thickness at the periphery of the collapse area. However, this is an unusual condition in that the transmissibility usually does not remain constant (confined water in gravel beds immediately above the bedrock is unusual in the district) with the drainage of the overburden adjacent to the collapse area.

CASE III, MOVEMENT OF WATER INTO CIRCULAR BROKEN BEDROCK AREAS

Since the common condition of flow of water into a circular collapse area involves some unwatering of the overburden at the edge of the collapse we should investigate that condition. Accordingly, let all the assumptions be the same as those in case II except that the overburden sand shall have a constant permeability "P" and the transmissibility shall decrease normally with the decrease in thickness of saturation.

Paralleling the steps of the preceding computation, the quantity of water moving at any radius (r) is:

$$Q - A(\pi R^2 - \pi r^2) = 2\pi r\, Py\, dy/dr$$

multiplying by dr/r,

$$Q\, dr/r - \pi AR^2 dr/r + \pi Ar dr = 2\pi P\, y dy$$

integrating,

$$(Q - \pi AR^2) \log_e r + \frac{\pi Ar^2}{2} = 2\pi Py^2/2 + C$$

evaluating C, at $r = r_o$ where $y = o$

$$(Q - \pi AR^2) \log_e r_o + \pi A r_o^2/2 = C$$

whence,

$$(Q - \pi AR^2) \log_e r/r_o + \frac{\pi A}{2} (r^2 - r_o^2) = \pi P y^2 \qquad (4)$$

substituting, $\pi AR^2 = K$, $Q = BK = \pi A(R^2 = r_o^2)$ in equation (4) as rewritten for points where $r = R$ and $y = Y$, and using the relations

$$r_o = \sqrt{K(1 - B)/\pi A} \quad \text{and } R = \sqrt{K/\pi A},$$

there follows:

$$K[(1 - B) \log_e (1 - B) + B] = 2\pi P Y^2$$

$$Y^2 = K/2\pi P [(1 - B) \log_e (1 - B) + B]$$

$$Y = R\sqrt{A/2P}\,[(1 - B)\, 2.3 \log_{10} (1 - B) + B]^{\frac{1}{2}}$$

Transmissibility varies with saturated

B	*Y/R √(A/2P)*
1.0	*1.0*
.9	*.818*
.8	*.691*
.7	*.582*
.6	*.483*
.5	*.392*
.4	*.306*
.3	*.225*
.2	*.147*
.1	*.056*
0	*0*

Table 17. Relationship of capacity "B" of circular bedrock area to accept water, to saturated thickness "Y" of adjacent overburden. Case III.

Under these assumptions the reduction in flow is much more rapid with the decrease in saturated thickness at the periphery of the collapse area than in the preceding case. and this is presumed to be the common condition that occurs on the Marquette range. In general, it may be stated that the flow of the water into the bedrock is approximately, though not perfectly proportional to the saturated thickness of the adjacent overburden under the conditions of lateral or radial flow that would occur in the vicinity of a circular or elongated collapse area.

Methods of control of ground water

Inasmuch as the prime purpose of the study of movement of ground water is to gain knowledge on the proper manner of control, consideration should be given to the methods and means of control.

In this report which deals essentially with ground water above the buried bedrock, only those methods of control which apply to these cases will be discussed. Water in the vicinity of mines and ore bodies may exist as surface or underground flows or combinations of both. Where surface water is the source of the mine water, the control methods that are commonly employed are either the diversion from the critical areas or transportation by means of flumes or pipes over the area. Where ground-water underflow is the source of mine water, the control problem becomes more difficult in that it cannot be always diverted or carried away from the area. In certain cases barriers or dams could be constructed to hold the ground water back and thus divert the flow to another outlet or channel of flow. The total costs of such structures would be large and in certain cases some details of construction have yet to be developed. The ideal barrier would be an impermeable wall from the land surface to bedrock and extending the width of the opening in the bedrock valley. To construct such a structure of concrete would require an excavation the length and depth of the valley and the complete unwatering to provide a watertight seal at the bottom. A barrier of sheet piling, while not requiring an excavation or unwatering, must have a tight seal at the bottom, and success in the construction of the seal would be influenced by the amount of rock in the overburden and the fractured nature of the bedrock surface. The use of grouts or chemical seals involve lesser material costs but the costs of drilling the grout holes on close spacing to accomplish complete cutoff may overbalance the saving in material costs. Neat cement grouts have been used in fissured and channeled rocks to control water flows, but are of little value in formations with fine pores, because of insufficient penetration of the grout through the pores. To obtain greater penetration in fine porous materials chemical products have been used on small scale projects such as shaft sinking and bridge caissons. The common chemicals are silicic acid gels, emulsified asphalt, and plastics which have a controlled time of set. The use of these chemicals requires that the grout-hole spacing be small when a penetration of the chemical into the formation is small. When a chemical which would penetrate to any distance is used, the cost of the chemical to impregnate a given diameter of cylinder must be balanced against the drill-hole spacing. The cost of the chemical can, in part, be offset by the construction of hollow cylinders (injecting the chemical and following it with an inert substance) instead of solid cylinders around each grout hole, but even with this type of construction the total costs are high. Freezing the ground to construct an ice barrier is also possible, given sufficient time and an adequate refrigeration system for the removal of heat from the ground. The construction of barriers involves a high initial cost and a low upkeep providing the barrier is distant enough not to be breached by subsidence in mining operations.

A plan involving a lesser initial cost and a greater operational cost has been tried by unwatering the porous materials and reducing the water level to such a low altitude that there is not sufficient saturated thickness to transmit a large quantity of water to the mined areas. Essentially this is a dry wall or dry barrier. Both vertical wells and infiltration galleries have been used successfully to accomplish this result, however this type of barrier requires an installation close to the point where maximum drawdown is needed or its usefulness is limited. Where it is desired to cause the ground-water "shoreline" to retreat down the buried-bedrock hillside and thereby unwater an area where ground water is entering the bedrock, either wells or infiltration galleries can be used when located where the yield will not drop off excessively as the unwatering proceeds. However, in the buried valley where the saturated material thickness is to be reduced to a minimum the yield of the wells is also reduced as the saturated thickness decreases. Thus in order to reduce the overall saturated thickness, it becomes necessary to construct a large number of points of withdrawal at close spacing. The construction of wells at close spacing which will have an ultimate small yield eliminates the need for expensive large diameter wells. A discussion of the ratio of yield of wells to diameter is found in the report "Ground-water problems of the Iron River district" page 55 and is summarized as follows:

1. "Under conditions in which the .depth of water in the aquifer is not greatly decreased by the pumping, the ratio of the quantity pumped by a large well to that by a small one is something less than the ratio between the logarithms of their respective radii. Under these conditions, which are typical for the early stages of pumping, the advantage of large wells is therefore small.

2. Under conditions in which a large part of the drawdown is caused by loss of head within the well, as by defective or corroded screens, wells of medium diameter are probably just, if led, inasmuch as the flow through the screen is proportional to the diameter.

3. As the water level is drawn down to the bottom of the aquifer, because of the very rapid decrease in transmissibility near the well the above equations do not hold, and a large well will have a much greater advantage than is indicated by the equations. However, even in this case, two or more smaller wells may be more economical"

A prerequisite to construction of many wells is the possibility of obtaining enough water from each to maintain the total yield necessary to draw the water level down to the point where the unwatering system will be a success. This is not easily accomplished on the Marquette range as the glacial till or hardpan above the buried bedrock is not at all places capable of transmitting a large quantity of water to a well. In fact, drilling at the Morris mine indicates that the odds of obtaining wells whose yields would be 25 gpm or over with a hundred feet of saturated thickness are poor. The general ratio of test holes to successful well installations for the Marquette range is about 10 test holes to each production well.

Ground-water Movement in the Bedrock

In this district only the water occurring in the iron-formation is of economic importance, probably because most of the mining is conducted within that formation. The water occurring in the slate footwall is negligible and for this reason that formation is considered to be impermeable. Water occurring in the conglomerate or quartzite hanging wall is generally in small amounts depending upon the degree of fracturing of the structure, and those rocks are considered as poorly permeable.

The permeable iron-formation which originally consisted of a permeable collection of sideritic cherts, grunerite-magnetite schists, and ferruginous cherts has been faulted, folded, and broken, and later oxidized to a ferruginous chert. In the most permeable zones, where commercial ore bodies were found, the silica was leached out and replaced by porous deposits of iron oxide, probably reducing the original overall permeability somewhat. The jointing and brecciation make the ore body permeable; probably in a large measure permeable in the same amount both parallel and perpendicular to the bedding. The ore may be considered somewhat hydrologically isotropic„ but the formation as a whole is isotropic probably to a leaser degree than the ore.

<u>Permeability of bedrock</u>

In following the law of conservation of energy, water makes preferential use of certain channels or formations where the resistance to flow is the least. The reciprocal of resistance to flow or permeability of the bedrock. Is dependent upon the size and number of openings capable of transmitting water. From observation in the mines permeability of the iron-formation is dependent on the capillary fracture and joint systems. Large vugs and solution channel systems are uncommon at the depths now mined, although it has been reported that many of the older and shallower mines encountered zones of very vuggy material. No large open fractures have been reported in any of the operating mines. although hydraulically-tight faults are common in the area, interconnected supercapillary fractures in the bedding of the major structures probably account for the largest percentage of water found in the mines where subsidence has not disrupted the flow pattern. Where subsidence has broken the bedrock the over-all permeability is greatly increased especially for those rocks such as the intrusives which originally had a very low permeability.

Table 18 lists the permeability and specific gravity of the different types of rocks in the Lake Superior district as obtained from core samples. The permeability of these samples are probably lower than the average values for the same bedrock in place, as the cores do not include the capillary and supercapillary fractures and joints which are largely responsible for the passage of water. In general the cores are the more resistant specimens of the rock which did not crumble when removed from the formation.

Field tests of the permeability of the bedrock in place at the Tracy mine were made using modified pumping test methods. Instead of withdrawing water from the bedrock, water was added to the drill holes at a constant rate, and the buildup of the water level was observed in the recharge drill hole and in adjacent holes. Similarly the decay of the recharge cone was observed when the addition of water ceased. The data was analyzed by the conventional formulas for pumping tests on wells in the "unconsolidated" overburden.

These vertical drill holes were in a grid at 300-foot intervals along 3 parallel lines 600 feet apart. The Tracy fault is about midpoint and perpendicular to the lines. In this area the formations dip about 45°. Owing to the dip only a few feet of the formation cut by one hole were intersected at depth (or vice versa) by an adjacent hole perpendicular to the strike. In general the transmissibility from hole to hole down dip and across the bedding is about equal to the transmissibility observed at the drill hole, but the transmissibility along the strike parallel to the bedding is about twice that observed in the other direction (See table 19). In other words the formations are not isotropic. No hydraulic interconnection between holes on the opposite sides of the Tracy fault were observed. This probably is caused by the impermeable dikes intruded in this area.

Laboratory tests of permeability could not be made from the cores from the same drill holes as were field tested, because the cores were split lengthwise for metallurgical analysis. However, a rough comparison of the permeability of the material in place with the laboratory values from other cores indicate that the material in place is 500 to 1,000 times as permeable as the core indicates. The reason for the large disagreement is obviously in the small size of the core tested.

In making field- tests of this type to obtain true values of the water-transmitting characteristics of the bedrock, care must be exercised in selection of the drill holes used. Holes having large portions lined or cemented, thus sealing zones of circulation, should be avoided. Newly finished holes are desirable because there has been less time for squeezing or caving of the lower sections of the hole. It is also desirable that the holes penetrate a large section of the saturated formation in order that the amount of the buildup of the water level in the hole be equivalent to only a small percentage of the total saturated thickness.

<u>Relation of structure to movement of water</u>

Field tests of the permeability of rock have indicated there is a greater permeability along the bedding and parallel to the strike than across the bedding. It follows that structure has an influence on the movement of water. Where the bedrock has been deformed, the joints, fractures, and fissures that developed are features which increase the permeability of the formation. Fold axes are loci of fracturing and are commonly the conduits through which ground water enters a mine. Examination of most areas in the mines that are producing water indicated that such areas were fractured zones within a fold structure.

FACTORS DIRECTING MOVEMENT

Permeability governs the amount of flow through the bedrock, but potential, gravity, and pressure are factors governing the direction of flow. Stated very simply all factors tend to move water from a higher value of the factor to a lower one; however, the distinction between the factors is not so simply stated. Gravity influences essentially downward movements either vertically or inclined, but pressure may influence movement in any direction as long as it is from a higher to a lower pressure. Potential is an expression of the energy of water attributable to its position in the formation, and its components involve altitude, pressure, and mass. In a partially saturated formation the pressure at the water surface is about zero and the movement is directed from a higher potential (pressure part of this factor is zero) to a lower one under a gravity gradient. In a completely saturated formation the movement is directed by the resultant of all the potential components to a region of lower value, but the movement may be in any direction unless impeded by an impermeable barrier. Pressure is important because it cannot fall significantly below zero and water can move horizontally only where a pressure gradient exists.

<u>General discussion</u>

In a synclinorium water moves by gravity down the pitch of the structure as well as down the limbs to the lowest point following zones of greatest permeability. Where deformation or intrusives exist across the flow path, the flow is impeded and a new path is taken in a zone whose permeability is less than the aquifer as a whole but greater than that of the obstruction, whatever it is. Pressure forces the water over arches and anticlines in the structure and where pressure exists there must be complete saturation of the formation. Mine workings tapping these formations where pressure exists have large initial flows of water which diminish rapidly after a short time. Mine workings tapping partially saturated sections of the bedrock have smaller flows that do not diminish after a period of time and generally the temperature of such water is colder than the normal bedrock temperature for that depth. While temperature is not a criterion for determining the source of water, those flows found in depth exceeding 600 feet below the land surface and whose temperatures are less than 48 or 50° F., are generally considered to be rapidly circulating waters whose sources probably are recharge from the bedrock contact with the glacial drift. The average temperature of the glacial drift water is about 44° F. and the temperature gradient is a little less than 1° per 100 feet in depth. Where mine waters with temperatures less than 52 are found from 1,000 to 2,000 feet below the land surface, those waters are generally considered to be from a source above the bedrock being mined.

Except for the initial flush flows of water encountered in newly developed sections of mine workings it is believed that most of the larger flows of water encountered in the mines of the district are those having sources generally beyond or outside the bedrock of the area. This is true especially in areas where subsidence has broken the bedrock and increased its permeability.

CHEMICAL QUALITY OF GROUND WATER

No complete investigation of the chemical quality of the ground water of the Marquette district was attempted as a part of this investigation, and the discussion of the quality is based on analysis of samples from typical formations. Analyses are shown on table 20 for the wells in the overburden and for flows from the bedrock formations. All the analyses were made by the Columbus, Ohio, laboratory of the U. S. Geological Survey, except those from the Humboldt test wells which were analyzed by the laboratory of the Cleveland-Cliffs Iron Co.

The analyses indicate that the ground water in the glacial overburden is similar in quality to that in the overburden in other parts of Michigan and Wisconsin and, except for hardness and iron, is of good quality for domestic and other common uses. The observed hardness ranges from 66 to 323 ppm, and the iron from 0.1 to 9.2 ppm, the water having the largest quantity of dissolved constituents generally coming from those wells that tap the deepest portion of the glacial overburden. The observed chloride content is low and ranges from 0.1 to 11 ppm. The sulfate content probably is slightly higher than the normal water from glacial overburden and ranges from 1 to 110 ppm. The sulfate is probably derived from decomposition products of pyrite in the slates and possibly some gypsum in the overburden materials. If water high in calcium sulfate is used in boilers without treatment, a hard scale forms.

The chemical quality of the water in Lake Sally (the source of supply for Ishpeming) and Teal Lake (the source of supply for Negaunee) is excellent. The hardness of each is low and the mineral content is considerably less than that found in municipal supplies elsewhere in the northern peninsula of Michigan.

The quality of water found in the bedrock is variable, however, the degree of mineralization increases with depth below land surface. A sample collected at a depth of about sea level is only slightly more mineralized than water in the glacial overburden; but, a sample collected below that altitude shows a greatly increased degree of mineralization. In general, chloride increases very rapidly with increase in depth, and the increase in chloride is at first accompanied by a proportional increase in sodium, but a further increase in chloride shows a greater increase in calcium rather than sodium. Water collected at about sea level altitude from the iron-formation contains a large amount of sulfate and calcium which is probably derived from the gypsum present in the iron ore at this altitude. All of the samples of water from the bedrock formations were taken in areas of slow ground-water circulation.

The waters of the eastern section of the district at the Maas mine are somewhat more mineralized than the overburden waters, but except for the calcium and sulfate ions are not as mineralized as the average ground water from this depth. The above-normal concentration of calcium and sulfate is probably due to the gypsum in the iron ore in this area. The analyses in this area indicate very little difference in mineralization of the water from the different geologic formations.

In the middle section of the Negaunee Basin the geologic section of the Negaunee iron-formation differs in that it contains a hard-ore strata which lies above the oxidized soft ores. The analyses indicate that the waters from each formation -- the overburden, hanging-wall quartzite. oxidized hard-ore, and unoxidized iron-formation -- become progressively more mineralized as each successively older formation is sampled, although the rate of increase is very small. The bottom of the oxidized soft-ore of the Negaunee iron-formation and the footwall contain 4 to 6 times the dissolved solids as the formations above, with most of the increase occurring in the ions of calcium, sodium, chloride, and sulfate. Part of the increase in mineralization is probably due to the increase in depth at which the last two mentioned samples were collected, although the footwall slates should contain more sulfate than the overlying formations owing to the pyrite included in the slate.

In the central section of the range the complete stratigraphic column could not be sampled from one mine location or adjacent properties. The hanging wall and oxidized iron-formation were sampled on the south limb of the synclinorium at the Greenwood mine, and the bottom of the soft-ore Negaunee iron-formation and the footwall slates were sampled on the north limb of the synclinorium at the Morris mine. The samples from the Greenwood mine contain the highest concentrations of sodium and chloride in the district and were sampled at about the same altitude as other points in the district. The concentrations of the calcium and magnesium ions are also higher than in other parts of the district, however the sulfate is very low. The waters from the bottom of the iron-formation and from the footwall at the Morris mine are slightly more-mineralized than water from the overburden. The concentrations of calcium and sulfate are high, but concentrations of sodium and chloride are low.

CONCLUSIONS

The purpose of the investigation of ground-water conditions near the iron mines of the Marquette range is to acquire enough data and to develop a theory by which it would be possible to predict with some degree of confidence how successful a program of control of ground water would be and how much water must be considered. To accomplish this aim requires a knowledge of (1) the source and occurrence of ground water, (2) location of the ground-water reservoirs and their relation to the iron-bearing formations, (3) transmissibility and storage coefficients of the glacial materials filling the buried valleys and (4) the theory of movement of the water in these materials toward sites of mining operations. An inventory of our knowledge of these phases would indicate the progress made and point out the remaining problems.

The original source of most ground water is precipitation which has seeped beneath the land surface and saturated all the porous formations below the water table. Where the pore spaces are freely interconnected circulation is active to and from the ground-water reservoirs.

The location of the ground-water reservoirs in the buried valleys has been closely delineated in the immediate neighborhood of the mines and ore bodies by means of a great number of test borings. In areas at a distance from the mines only general features can be determined and the continuity of the buried valleys cannot be definitely established except by inference based on known erosional resistance of the bedrock strata. Hence there is sufficient information to define the immediate boundaries of the ground-water reservoirs near the mines, but some of the distant boundaries are not known with certainty.

The transmissibility of the glacial overburden has been determined from pumping tests that have been made in those areas where surface unwatering wells have been installed. It ranges from 3,000 to 85,000 gallons a day per foot depending largely on the depth of saturation. The average for the district is probably less than 20,000 gpd/ft. The average permeability is about 100 gallons a day per square foot which is low for glacial overburden materials, but it is caused by the poor sorting of the materials and the presence of considerable quantities of silt and clay. No geologic criteria for the location of high yield wells were developed as the deposition of the glacial materials was discontinuous and incomplete. Exploratory drilling for wells for unwatering the overburden generally revealed porous materials at the land surface capable of accepting and yielding quantities of ground water, but at greater depth poorly permeable materials are generally found which will yield little water to wells or to the bedrock below.

In general theory of movement of water in the overburden to the mines has been given . It is indicated that the maximum reduction of the water level in the critical areas requires unwatering devices to be located close to those areas, and that such devices would divert maximum amount of water from the points of entry into the mines with the least amount of pumping. A system of cheaply constructed wells near collapsed areas, even though they might be eventually lost through further collapse, might be more economical as an unwatering device than larger wells of greater capacity located at some distance from the collapse area.

Theory indicates that the flow of water into the bedrock varies approximately as the saturated thickness in the overburden. In the Marquette district the system of reducing the head in the overburden, by use of vertical wells and infiltration galleries, is effective in reducing the head in proportion to yield. In general, controlling the water by pumping from the overburden is effective in reducing the flow of water into the bedrock below.

Water in the bedrock is usually in minor amounts except in certain cases where it is stored within the fractures and supercapillary systems of the bedrock structure. The bedrock permeability as determined from field tests and laboratory tests on cores is low, and except where subsidence has broken the structure and increased the permeability the amount of water entering a typical mine is only a few hundred gallons a minute.

Chemical analyses show that the water in a glacial overburden is a moderately mineralized calcium bicarbonate water. Water from the upper workings of the mines are of a similar nature but the degree of mineralization increases with the depth.

Many problems of control have yet to be solved -- the manner of obtaining large yields in wells from poorly permeable materials, the manner of diversion of water from the ore-bearing zones, and the problems of construction of successful drainage systems without the high operating costs such as for system of wells.

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Gage located 2,200' S. and 300' W. of NE cor. sec. 1, T. 47 N., R. 28 W.

Month	Daily discharge in cubic feet per second				Monthly runoff in inches	Discharge in million gallons per day per square mile
	Maximum	Minimum	Mean	Per square mile		
1949						
Jan.		0	0.05 *	0.045*	0.052*	0.0291*
Feb.		0	.05 *	.045*	.047*	.0291*
Mar.		0	.1 *	.090*	.104*	.0582*
Apr.	1.094	0.086	.405	.365	.406	.2358
May	.865	.268	.464	.418	.482	.2702
Jun.	.835	.346	.526	.474	.529	.3064
Jul.	3.112	.562	1.152	1.038	1.197	.6709
Aug.	1.566	.660	.919	.828	.955	.5352
Sept.	.955	.646	.736	.663	.740	.4285
Oct.	.805	.660	.698	.629	.728	.4065
Nov.	1.030	.775	.848	.764	.852	.4938
Dec.			.9 *	.811*	.935*	.5242*
The year.	3.112	0	.571	.514	7.024	.3322
1950						

Jan.			.9 *	.811*	.935*	.5242*
Feb.			.9 *	.811*	.845*	.5242*
Mar.			1.0 *	.901*	1.039*	.5823*
Apr.	1.33		1.286	1.159	1.293	.7491
May	19.45	1.27	6.781	6.109	7.043	3.9484
Jun.	5.80	3.05	3.807	3.430	3.827	2.2169
Jul.	3.50	2.19	2.456	2.213	2.552	1.4303
Aug.	2.95	1.47	2.060	1.856	2.140	1.1996
Sept.	1.45	1.07	1.200	1.081	1.206	.6987
Oct.	1.17	1.05	1.091	.983	1.133	.6353
Nov. 1-14	1.13	1.17	1.2 *	1.081*	1.206*	.6987*
Dec.			1.1 *	.991*	1.143*	.6405*
The year.	19.45	1.05	1.982	1.786	24.362	1.1543

Drainage area 1.11 square miles above gage.

*Record estimated because of ice.

Table 11. Discharge of Carp River near North Lake, Michigan.

Gage located 1,700' W. and 300' N. of SE cor. sec. 3, T. 47 N., R. 27 W.

Month	Daily discharge in cubic feet per second				Monthly runoff in inches	Discharge in million gallons per day per square mile
	Maximum	Minimum	Mean	Per square mile		
1948						
Sept.	0.18	0.03	0.070	0.035	0.039	0.0226
Oct.	.14	.02	.059	.030	.034	.0194
Nov.	.73	.07	.374	.187	.209	.1209
Dec.			.5 *	.25 *	.288*	.1616*
1949						
Jan.			.5 *	.25 *	.288*	.1616*
Feb.			.4 *	.20 *	.208*	.1293*
Mar.			.7 *	.35 *	.404*	.2262*
Apr.	16.0	1.42	6.85	3.42	3.816	2.2104
May	14.3	.75	2.86	1.43	1.649	.9242
Jun.	1.95	.22	.712	.356	.397	.2301
Jul.	76.7	.35	6.10	3.05	3.516	1.9713
Aug.	11.9	.45	2.23	1.12	1.291	.7239
Sept.	8.93	.41	1.74	.870	.971	.5623
Oct.	1.85	.60	.983	.492	.567	.3180
Nov.	4.47	.98	1.87	.935	1.043	.6043
Dec.			1.0 *	.5 *	.576*	.3232*
The year.	76.7	.22	2.162	1.081	14.726	.6987
1950						
Jan.			.8 *	.4 *	.461*	.2585*
Feb.			.7 *	.3 *	.312*	.1939*
Mar.			.8 *	.4 *	.461*	.2585*
Apr.	5.6	.61	2.05	1.025	1.144	.6625
May	35.0	.48	13.4	6.700	7.724	4.3303

Jun.	10.6	.53	1.97	.985	1.099	.6366
Jul.	1.49	.24	.448	.224	.258	.1448
Aug.	4.92	.18	.928	.464	.535	.2999
Sept.	.51	.10	.204	.102	.114	.0659
Oct.	.18	.14	.153	.0765	.088	.0494
Nov.	.68	.18	.280	.140	.156	.0905
Dec.			.4 *	.2 *	.231*	.1293*
The year.	35.0	.10	1.844	.922	12.583	.5959

Drainage area 2.00 square miles above gage.

*Record estimated because of ice.

Table 12. Discharge of Partridge Creek at Ishpeming, Mich.

Gage located 700' N. and 300' E. of SW cor. sec. 5, T. 47 N., R. 26 W.

Month	Daily discharge in cubic feet per second				Monthly runoff in inches	Discharge in million gallons per day per square mile
	Maximum	Minimum	Mean	Per square mile		
1948						
Aug.	5.99	1.72	2.19	0.893	1.030	0.5771
Sept.	3.88	1.36	1.74	.709	.791	.4582
Oct.	2.94	1.28	1.49	.607	.699	.3923
Nov.	4.20	1.32	1.76	.717	.800	.4634
Dec.			1.6 *	.652*	.752*	.4214*
1949						
Jan.			1.6 *	.652*	.752*	.4214*
Feb.			1.6 *	.652*	.679*	.4214*
Mar.			1.8 *	.734*	.846*	.4744*
Apr.	4.08	2.73	3.34	1.362	1.519	.8803
May	6.20	2.64	3.14	1.280	1.476	.8273
Jun.	3.80	2.00	2.44	.995	1.110	.6431
Jul.	11.00	1.64	3.15	1.284	1.480	.8299
Aug.	5.71	1.82	2.92	1.190	1.372	.7691
Sept.	7.01	1.82	2.60	1.060	1.183	.6851
Oct.	4.63	1.54	2.37	.966	1.114	.6243
Nov.	3.66	1.74	2.32	.946	1.056	.6114
Dec.			2.1 *	.856*	.987*	.5532*
The year.	11.00	1.54	2.48	1.011	13.574	.6534
1950						
Jan.			2.0 *	.815*	.940*	.5267*
Feb.			1.9 *	.775*	.807*	.5009*
Mar.			2.2 *	.897*	1.034*	.5797*
Apr.	7.88	4.63	5.68	2.316	2.582	1.4969
May	12.4	4.08	6.03	2.458	2.834	1.5886
Jun.	4.75	2.48	3.58	1.459	1.628	.9430
Jul.	7.29	1.64	2.30	.938	1.081	.6062
Aug.	4.20	1.82	2.34	.954	1.100	.6166
Sept.	2.91	1.50	1.83	.746	.832	.4822

Oct.	1.92	1.54	1.66	.677	.781	.4376
Nov.	3.18	1.50	2.05	.836	.933	.5403
Dec.			2.0 *	.815*	.940*	.5267*
The year.	12.4	1.50	2.798	1.140	15.492	.7368

Drainage area 2.453 square miles above gage.

*Record estimated because of ice.

Table 13. Discharge of Partridge Creek at Negaunee, Mich.

Date of test	Pumped well no.	Observation well no.	Coefficient of transmissibility (gpd/ft)	Coefficient of storage	Duration of test (days)	Distance from observation well to hydro-geological recharge boundary (ft)
			Morris mine area			
3-30-48	P.W. 1	P.W. 1	25000	--	1	
	do.	T.W. 509	28,200	0.08	1	
3-31-48	P.W. 2	W.W. 2	11,050	--	1	
1-16-48	P.W. 3A	T.W. 528	60,000	.002	17	2,420
	do.	T.W. 512	14,200	.0091	17	630
	do.	P.W. 3A	11,000	--		
9-10-47	P.W. 5	P.W. 5	22,500	--	70	
	do.	T.W. 518	12,000	.031	70	
	do.	P.W. 6	38,000	.082	70	900
	do.	T.W. 503	24,800	.055	70	610
	do.	T.W. 526	18,600	.101	70	610
4- 6-48	P.W. 9	P.W. 9	8,800	--		
	do.	T.W. 504	12,700	.31	1	
5-13-47	P.W. 10	P.W. 10	47,000	--	70	
1- 7-48	do.	do.	54,500	--	9	
5-13-47	do.	T.W. 528	85,000	.41	70	
5-13-47	do.	T.W. 532	40,300	.139	70	
8-18-50	P.W. 19	T.W. 519	4,250	.00004	1/4	1,000
	do.	T.W. 503	4,710	.00022	1/4	420
	do.	T.W. 526	3,070	.00034	1/4	460
		Average	26,270	.094		
			Mather mine area			
3-18-48	P.W. 1	P.W. 1	8,480	--	1/2	
			Humboldt area			
10-13-	T.W. 5	T.W. 5	20,000	--	1/6	
10-20-	T.W. 6	T.W. 6	7,000	--	1/6	
11- 4-	T.W. 10	T.W. 10	13,500	--	1/6	
11-11-	T.W. 12	T.W. 12	9,000	--	1/6	
		Average	12,370			
			West Ishpeming area			
7-22-49	T.W. 1	T.W. 1	5,000	--	1/6	
8-22-49	T.W. 2	T.W. 2	3,500	--	1/6	
9-28-49	T.W. 3	T.W. 3	4,000	--	1/6	
		Average	4,200			

Table 15. Coefficients of transmissibility and storage of the glacial overburden as computed from pumping tests in the Marquette district.

Sample No.	District	Mine or Exploration	Hole No.	Depth (ft)	Material	Specific gravity	Coefficient of permeability (Meinzer's unit[1/])
1	Iron River	Buckholtz	5	190	Hanging-wall feldspathic graywacke, coarse-grained	2.75	0.00006
2	Iron River	Buckholtz	5	708	Hanging-wall dark coarse-grained graywacke	2.84	.0000054
3	Iron River	Buckholtz	5	745	Hanging-wall slate, thin bedded	2.85	.000016
4	Iron River	Buckholtz	5	870	Hanging-wall dark gray non-graphitic slate	2.90	2/
5	Iron River	Buckholtz	5	965	Hanging-wall, near iron-formation, thin banded dark slate	2.86	.000028
6	Iron River	Buckholtz	5	970	Chert, top of iron-formation	2.68	.0000035
7	Iron River	Buckholtz	5	980	Quartz-seamed black slate (fault zone)	2.76	.94
8	Iron River	Buckholtz	18	290	Hanging-wall graywacke, leached and kaolinized	2.75	.000095
9	Iron River	Buckholtz	21	295	Hanging-wall graywacke, leached, with red seams	2.83	.00035
10	Iron River	Sherwood	T-4	1,050	Hanging-wall, graphitic slate with chert fragments	3.17	.0000094
11	Iron River	Cronin	1	325	Hanging-wall graywacke, oxidized	2.97	.000011
12	Iron River	Hiawatha	C-A-47	948	Magnetic ironstone	3.21	0.000017
13	Iron River	Hiawatha	C-A-47	1,080	Hanging-wall graywacke, massive , dark	2.90	.00011
14	Iron River	Tully	G-51	110	Hanging-wall slate, oxidized	3.63	.000029
15	Iron River	Wauseca	908-52	130	Hanging-wall slate, deeply oxidized	3.36	.000041
16	Iron River	Cardiff	3-50	330	Hanging-wall slate, massive, light gray	2.79	.000009
17	Iron River	Pacific Isles	P-2	240	Hanging-wall graphitic slate, with chert nodules	3.14	.0012
18	Iron River	Buckholtz	19	505	Quartz-seamed black slate	2.96	3.3
19	Iron River	Sherwood	T-4	520	Iron-formation breccia, very slightly oxidized chert-carbonate	3.42	.0015
20	Iron River	Sherwood	T-4	575	Slaty iron-formation, oxidized, with black slate seams	3.68	.0013
21	Iron River	Sherwood	T-4	865	Oxidized cherty hematitic iron-formation	3.79	.0026
22	Iron River	Sherwood	T-4	1,140	Iron-formation, unoxidized (upper slaty)	--	.000071
23	Iron River	Sherwood	T-4	1,220	Iron-formation, oxidized slaty	3.70	.063
24	Iron River	Sherwood	T-7	480	Soft hematitic ore	4.84	0.0049
25	Iron River	Sherwood	T-7	580	Oxidized cherty iron-formation, cherty hematite	3.32	.0044
26	Iron River	Sherwood	T-8	660	Oxidized iron-formation, chert-hematite	3.52	.000027
27	Iron River	Sherwood	T-8	780	Unoxidized iron-formation, chert-carbonate	3.07	.000002
28	Iron River	Sherwood	T-8	930	Unoxidized carbonate, from iron-formation	3.37	.000033
29	Iron River	Sherwood	T~13	550	Oxidized iron-formation, chert-hematite	3.87	.00008

30	Iron River	Sherwood	T-13	620	Limonite-hematite ore	4.73	.000033
31	Iron River	Sherwood	T-13	655	Iron-formation, oxidized, chert-limonite	3.27	.000086
32	Iron River	Sherwood	T-14	925	Oxidized iron-formation	3.23	.0007
33	Iron River	Campbell	CS-7	510	Oxidized iron-formation, chert-limonite	3.41	2/
34	Iron River	Campbell	CS-7	760	Oxidized iron-formation, chert-hematite	4.17	.0092
35	Iron River	Campbell	CS-5	770	Unoxidized iron-formation, chert-carbonate	3.27	0.000018
36	Iron River	Hiawatha	WHJ-51	70	Hard goethitic ore	4.18	.000012
37	Iron River	Bengal	C-51	365	Limonite ore	4.13	.00026
38	Iron River	Pacific Isles	P-2	150	Unoxidized iron-formation	2.99	.0013
39	Iron River	Pacific Isles	P-4	190	Massive carbonate, from upper part of iron-formation	3.43	.000062
40	Marquette	Mather B	153	70	Hematitic goethitic ore, granular	3.83	.0013
41	Marquette	Mather B	142	122	Hematitic cherty iron-formation, thin bedded	3.41	.000045
42	Marquette	Mather B	142	245	Hematitic cherty iron-formation	3.91	.000036
43	Marquette	Mather B	142	253	Hematitic goethitic cherty iron-formation	3.85	.00016
44	Marquette	Cambria	204	110	Soft ore, granular	3.94	.000074
45	Marquette	Cambria	204	281	Hematitic argillaceous cherty iron-formation	3.12	.033
46	Marquette	Cambria	208	218	Hematitic argillaceous cherty iron-formation	3.43	.000072
47	Marquette	Cambria	209	218	Hematitic argillaceous cherty iron-formation	3.11	2/
48	Marquette	Maas	74	5	Soft ore, granular	4.50	.018
49	Marquette	Maas	74	24	Hematitic goethitic ore	3.91	.00011
50	Marquette	Maas	74	110	Hematitic soft ore, granular	4.81	.04
51	Marquette	Cliffs Shaft	761	150	Hard hematitic cherty jasper iron-formation	3.39	.0000073
52	Marquette	Cliffs Shaft	762	50	Conglomerate ore	4.37	.0000028
53	Marquette	Cliffs Shaft	764	65	Magnetic hard ore	4.73	.0000033
54	Marquette	Cliffs Shaft	839	839	Magnetic hard ore	5.05	.000021
55	Marquette	Sec. 5	37	180	Hematitic goethitic cherty iron-formation	3.01	.19
56	Marquette	Sec. 9	71	259	Hard hematitic cherty iron-formation	4.61	.7
57	Marquette	Sec. 11	15	700	Hematitic cherty iron-formation	3.03	.0085
58	Marquette	Cascade	4	1,070	Hard hematitic jasper cherty iron-formation	4.01	2/
59	Marquette	Tilden	22	120	Hematitic cherty iron-formation	3.48	2/
60	Iron River	Sherwood	T-1	340	Footwall siltstone	3.05	.00093
61	Iron River	Sherwood	T-1	475	Footwall siltstone, very slightly oxidized	2.89	0.000031
62	Iron River	Sherwood	T-1	535	Footwall graphitic slate	2.93	2/
63	Iron River	Sherwood	T-1	615	Footwall graphitic slate. Laminated, probably slightly deteriorated.	2.98	2/

64	Iron River	Sherwood	T-1	730	Greenish dike rock	2.88	.000067
65	Iron River	Sherwood	T-1	765	Footwall banded sericitic slate	2.99	.000054
66	Iron River	Sherwood	T-2	295	Footwall sericitic slate	2.97	.00083
67	Iron River	Sherwood	T-3	280	Footwall slate, interbedded sericitic and pyritic	3.04	.000012
68	Iron River	Sherwood	T-3	320	Footwall graphitic slate	3.05	.000023
69	Iron River	Sherwood	T-3	500	Footwall siltstone, some vein quartz	2.89	2/
70	Iron River	Sherwood	T-10	500	Footwall graphitic slate (chert breccia)	2.90	.0000043
71	Iron River	Bengal	22	930	Graywacke with chert fragments. oxidized	3.85	.0014
72	Iron River	Hiawatha	501	605	Graywacke-chert breccia	3.13	.00002
73	Iron River	Hiawatha	501	950	Iron-formation breccia, unoxidized (chert-carbonate)	3.22	.0000056
74	Iron River	Grossbusch	11	620	Graywacke	2.89	.0028
75	Marquette	Sec. 9	58	1,875	Quartzite	2.71	.000035
76	Marquette	Republic	7	14	Mica schist	3.25	.000039
77	Marquette	Sec. 9	61	239	Conglomerate	2.91	.00051
78	Marquette	Sec. 11	201	2,015	Intrusive	2.99	.000016
79	Marquette	Humboldt	4	145	Intrusive	2.87	.0000016
80	Marquette	Sec. 11	23	505	Intrusive	2.98	.000058
81	Marquette	Humboldt	1	35	Magnetic intrusive	3.20	.000031

1/ Meinzer's Unit: gallons per day through cross-sectional area of 1 square foot under hydraulic gradient of 100 percent at a temperature of 60°F.

2/ Impossible to obtain unfractured sample for testing.

One Meinzer unit equals 54.8 millidarcies.

Table 18. Laboratory coefficients of permeability and specific gravity of rock formations of the Lake Superior district.

Drill hole no.	820	821	824	825	829	835	837	736	604
Depth of holes in feet	1,104	1,390	1,251	1,031	1,456	510	597	2,578	1,499
Feet of iron-formation in hole	1,024	1,236	1,152	954	1,279	394	336	1,428	796
Feet of dike in hole	33	30	39	62	53	--	--	890	549
Feet of slate in hole	30	113	46	--	100	93	230	248	118
Transmissibility of hole	190	222	310	550	273	289	126	320	15
Transmissibility along strike	791	450	651	787	578	516	432	--	--
Coefficient of storage	0.0006	0.0004	0.0003	0.0002	0.0004	0.0005	0.0006	--	--
Average permeability of hole	.17	.16	.25	.54	.19	.59	.22	.12	.01
Average permeability along strike	.73	.33	.53	.77	.40	1.06	.76	--	--

All drill holes located in T. 47 N., R. 26 W.

Table 19. Values of permeability of bedrock obtained by modified pumping test methods 1/.

1/ Meinzer's Unit.