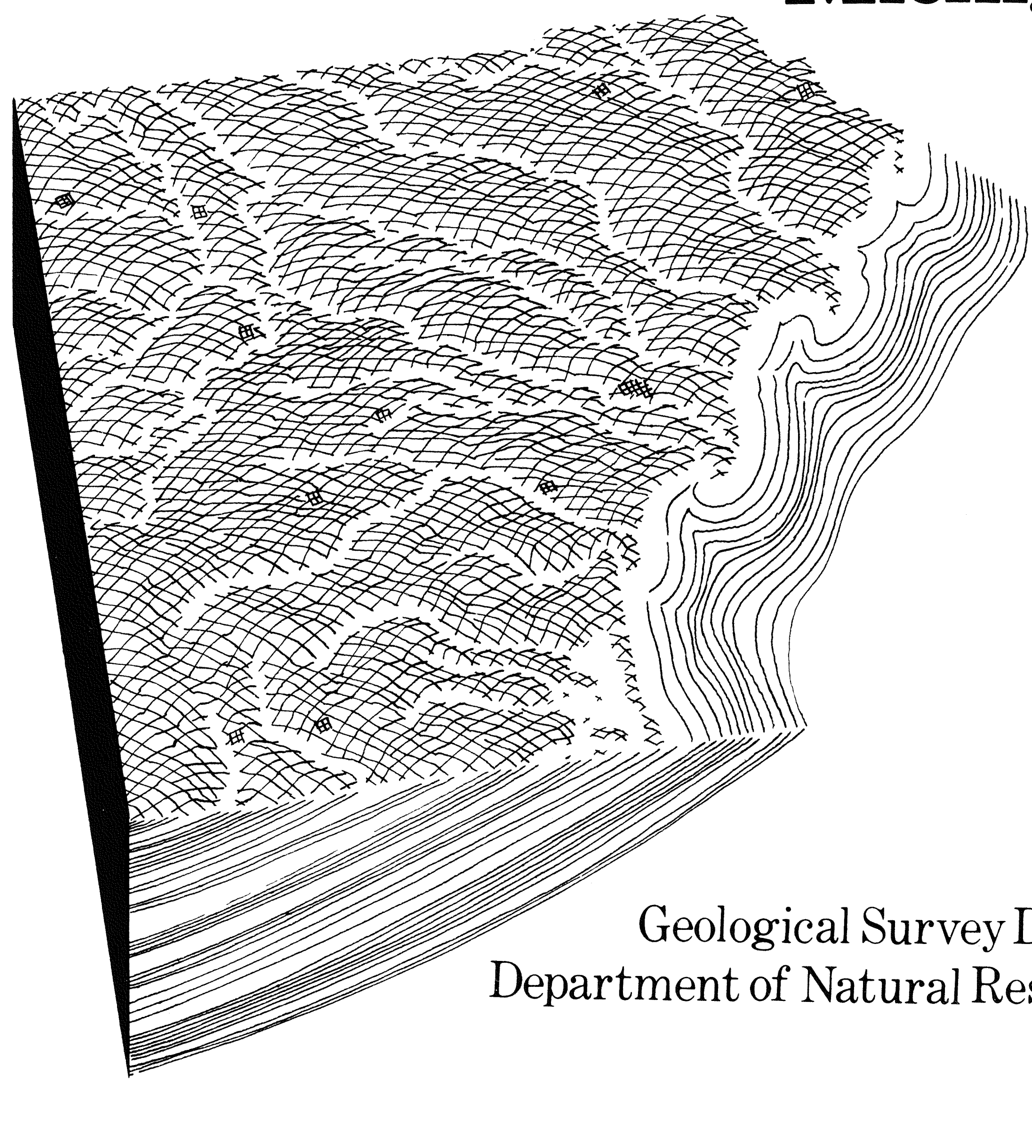
Report of Investigation 13

Geology for Environmental Planning in Monroe County, Michigan



1970

Geological Survey Division

Department of Natural Resources

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GEOLOGY FOR ENVIRONMENTAL PLANNING IN MONROE COUNTY, MICHIGAN

by
Andrew J. Mozola

Prepared in cooperation with the
Department of Geology
Wayne State University
Detroit, Michigan
1970

PREFACE

This report summarizes the surface and subsurface geology of Monroe County. The series of maps accompanying the report are based upon an extensive collection of well records and test boring data. Although the sources of these records are too numerous to acknowledge individually, each contribution is gratefully appreciated. Principal contributors to this project include Mr. Olen Marshall (water well contractor), Mr. James E. Akers of the Monroe County Health Department, the state Geological Survey Division, and the Michigan Department of State Highways.

The author is indebted to Mrs. Patricia L. Mozola for transcribing the many well and test boring records, and for field assistance in pinpointing their exact locations on base maps. In all mapping projects, much tedious labor is involved plotting, checking, and revising to achieve a satisfactory final product. These tasks were diligently performed by Messrs. Dan W. Walchak and Jon E. Salsburg, undergraduate students in the Department of Geology. Finally, the author is extremely grateful to Mr. Robert W. Kelley of the Michigan Geological Survey for editing both maps and manuscript for publication.

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GLOSSARY

Alluvium -- Clastic sediments resulting from stream deposition.

Aquifer -- Water bearing formation.

Basement complex -- Rock series of complex composition and structure beneath a sedimentary sequence. Usually Precambrian, but occasionally younger.

Calcareous -- Containing calcium carbonate (CaCO3).

Carbonate -- A salt or ester of carbonic acid; compound containing the radical CO3.

Clastic -- Textural term applied to rocks composed of fragmental materials usually derived by weathering from pre-existing rocks.

Contact -- Place, or surface, where two different kinds of rocks are adjacent to each other.

Dip -- Angle at which a stratum or any planar feature departs from the horizontal. Dip is perpendicular to the strike.

Drift -- Term applied to all materials of glacial origin, whether deposited directly from the ice or in melt water.

Evaporite -- Salts deposited as the result of complete evaporation of the solvent. Natural salts are usually impure due to the inclusion of other non-soluble sediments.

Exposure -- That portion of a rock unit exposed to view.

Glaciofluvial -- Pertaining to waters flowing from glaciers or to deposits resulting therefrom.

Glaciolacustrine -- Pertaining to glacial lake conditions or to sediments deposited in lakes marginal to a glacier.

Glacial spillway -- Outlet for glacial melt waters.

Inlier -- Patch of older rocks surrounded by younger strata. Also called a window. Converse of "outlier".

Interlobate -- The area situated between ice lobes.

Lacustrine -- Produced by, belonging to, or associated with lakes.

Lithology -- Description of rocks based on the study of mineral constituents, textures, and primary structures.

Outcrop -- That portion of a rock unit appearing at the surface, or immediately beneath the soil cover.

Outlier -- Patch of detached or isolated strata surrounded by older strata.

Outwash -- Stratified sediments deposited by melt water issuing from a glacier.

Overburden -- Unconsolidated materials resting directly on bedrock.

Permeability -- The capacity of rocks or unconsolidated sediments to transmit fluids.

Piezometric surface -- The surface to which water from a given confined aquifer will rise under its full head.

Porosity -- Percent of pore space in a rock or soil to its total volume.

Potable -- Suitable for human consumption.

Stratigraphy -- Description and correlation of layered rocks.

Strike -- The bearing of the line formed by the intersection of an inclined stratum with the horizontal plane of reference. Strike is perpendicular to dip.

Subsurface -- Below the land surface.

Tectonic -- Pertaining to rock structures resulting from the deformation of the earth's crust.

Till -- Nonsorted, nonstratified drift carried or deposited by a glacier.

Unconformity -- Surface representing erosion or non-deposition between two rock strata.

Water table -- Upper surface of the water saturated zone in drift and bedrock.

Window -- See "inlier".

GEOLOGY FOR ENVIRONMENTAL PLANNING IN MONROE COUNTY, MICHIGAN

ABSTRACT

Monroe County, situated in the extreme southeast corner of Michigan, is underlain by Paleozoic rock strata dipping gently northwest. The bedrock stratigraphic sequence consists largely of carbonate rocks with some sandstones and shales. The bedrock surface is almost completely veneered by glacial drift varying in thickness from a few inches to nearly 160 feet. Over most of the county, however, the drift is considerably less than 30 feet. Only a few natural rock exposures occur at widely scattered localities. Throughout most of the county, except principal urban areas, domestic water supplies are obtained primarily from wells completed in bedrock; and wastes are deposed in septic tanks. The ground-water resource, therefore, is particularly vulnerable to contamination. Knowledge of geologic conditions then becomes a crucial consideration in land-use planning. Accompanying the report is a series of half-inch-to-mile county maps depicting bedrock geology, bedrock topography, drift thickness, glacial geology, and piezometric water level. A small bedrock map of the state and a stratigraphic nomenclature chart are also included.

GENERAL INFORMATION

The county of Monroe, bordering Lake Erie in the extreme southeast corner of Michigan, is situated approximately midway between the cities of Detroit, Michigan and Toledo, Ohio. Consequently the future development of the county undoubtedly will be influenced by these two metropolitan areas. According to the Comprehensive Development Plan (Monroe County Planning Commission, 1965-66) the county population in 1960 was reported as 101,129 inhabitants; and by 2000, is expected to reach anywhere from 240,000 to 805,000, depending upon the method of projection used. Of its total land area of 562 square miles (359,000 acres), nearly 11 percent (37,700 acres) has been designated as "built-up" with the remaining 89 percent classified as agricultural (315,324 acres) and marginal or vacant land (6,572 acres).

Geology

Underlying the county are Paleozoic strata that dip gently to the northwest and consist largely of limestones and dolomites (carbonate rocks) with some sandstones and shales. The bedrock surface is not flat, but highly irregular, and features numerous valleys and ridges originating prior to, and during, Pleistocene glaciation. Glacial drift, resting directly on the Paleozoic strata, varies in thickness from a very thin layer of only a few inches up to nearly 160 feet (near the northwestern corner). Over much of the area the thickness of this cover is considerably less than 30 feet. A few natural rock exposures occur at widely scattered localities, some along principal streams. The glacial drift consists mainly of clay till reworked by glacial lake water and veneered by lacustrine sands, silts, and clays.

Topography

The county is essentially a plain of very low relief sloping southeast, from a maximum elevation of 730 feet in the northwest corner to 572 feet at Lake Erie. This gradual change in elevation, 158 feet in a distance of nearly 26 miles, reflects the low velocities of the streams. Ditches are required to accelerate the drainage.

Water Supply

Much of the county is not served by public water or sewer facilities. Public water systems are established in the following towns: Monroe (Lake Erie source), Dundee (Raisin River source), and in Carleton, Petersburg, Milan, and South Rockwood (bedrock wells). The remainder of the county depends on individual domestic wells and, to a minor extent, on community wells. Due to the high clay content and thinness of the drift, more than 90 percent of the wells are completed in bedrock. Satisfactory well completions in drift are feasible only in areas of thicker drift cover.

Sewerage

Public sewer facilities are established in Milan, Dundee, Carleton and the City of Monroe, the latter also serving small contiguous areas. The remaining areas depend on individual domestic septic tank systems which, according to an estimate by the National Sanitation Foundation (1964), numbered 18,000 units in the county (one per 20 acres, or, one per 5.6 habitants). Because of shallow bedrock depth, flat topography, and the rural nature of most of the area, the Comprehensive Development Plan (Monroe County Planning Commission, 1965, Vol. 2) states "it is anticipated that the majority of the Regional Planning Area, especially within the central portions which are predominantly agricultural in nature, will remain unserved by public water and sewer facilities for a considerable period of time". Septic tanks and their tile fields are systems that, in a sense, "rain" several times daily when in use. Hence, in time an increasing population will seriously contaminate the ground-water resource. In metropolitan areas, agricultural lands are yielding to subdivision developments, particularly, those lands with soils having favorable percolation rates--a basic requirement for the proper functioning of septic tank systems. Obviously, in a thinly mantled carbonate rock terrane as in Monroe County, the ground-water resources are very susceptible to contamination from the ground surface. A number of possible sources will be discussed later.

BEDROCK GEOLOGY

Relation to Michigan Basin

Monroe County occupies a position along the southeast rim of the Michigan structural basin (see small scale map 2). In this sector the sedimentary strata outcrop as irregular and varying bands trending northeast-southwest. The rock layers incline (dip) gently northwest, therefore, become progressively younger in age, geologically speaking, from southeast to the northwest (section B-B1 on small scale map 2). The major physiographic features of the bedrock surface for the Lower Peninsula consist essentially of dissected uplands and lowlands; the former with elevations ranging between 650 and 1000 feet, and the latter, between 400 and 650 feet above sea level. The county is situated within the Erie-Huron Lowland of southeastern Michigan (Fig. 1).

Stratigraphy

The bedrock consists entirely of sedimentary rock originating in ancient marine seas that occupied the area during the Paleozoic Era. The stratigraphic succession (from youngest to oldest) ranges from the Antrim Shale of Upper Devonian age to the Eau Claire and Mount Simon sandstones of Late Cambrian age. Oil and gas well logs indicate that the total section is anywhere from 2500 to 3500 feet in thickness depending upon location within the county. The Paleozoic strata, in turn, rest on a Precambrian basement complex composed mostly of crystalline rocks of igneous and metamorphic origin (Chart 1). The only bedrock actually outcropping beneath the drift, however, consists of Paleozoic strata from the Salina Group (Late Silurian) through the Antrim Shale (Late Devonian). Descriptions of these units are given in the Appendix. Strata older than the Salina are encountered only in deep wells or test borings.

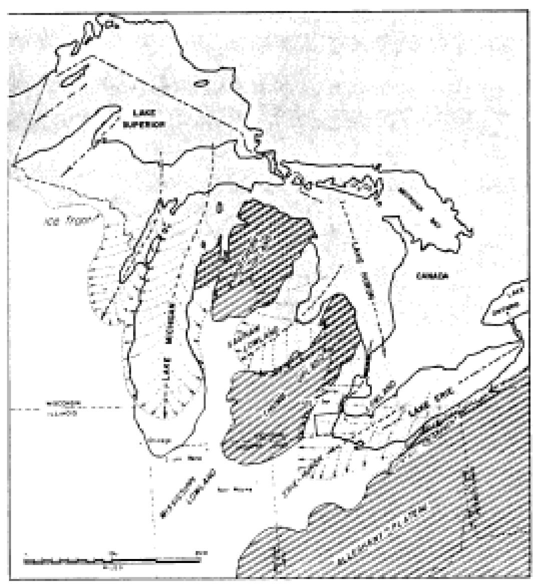

Figure 1. Topographic uplands and lowlands influenced the deployment of ice lobes along the glacier front.

Sedimentary rocks are broadly subdivided into two main categories--clastic and nonclastic. Clastics include rocks formed dominantly of consolidated fragments of pre-existing rocks and mineral matter. Examples include conglomerates (from gravel), breccias (from angular fragments), sandstones (from sand), siltstone (from silt), and shale (from clay). Differentiation is mostly by texture and grain size. Depending on the sorting efficiency of geological processes during deposition, admixtures of various grain size are not uncommon. Hence, lithologies as silty sandstones, sandy shales, etc., appear in the stratigraphic sequence. Nonclastics on the other hand, consist largely of chemically- and/or biochemicallyprecipitated salts derived from sea water.

When subsequently indurated these rocks are characterized by a crystalline texture, rather than fragmental grains. Examples include gypsum, anhydrite, salt (evaporite deposits); limestones and dolomites (carbonates). Differentiation of nonclastics is based on chemical or mineral composition. Most clastic sedimentary rocks contain varying amounts of precipitated salts, usually as a cementing agent, whereas most nonclastic rocks contain some clastic materials. Hence, sedimentary rocks of high chemical purity or very uniform physical bulk characteristics are exceptions rather than the general rule. Such deposits constitute some of our important nonmetallic resources. Their recognition and development should be encouraged through proper land use zoning.

Chart I provides both outcrop and subsurface nomenclatures in common usage. Most formation terms are based on studies of surface exposures because actual rock exposures are always accessible for re-examination. Naming formations occurring in the subsurface depends entirely upon the availability of rock cuttings and cores. Frequently subsurface terminology does not correspond with surface outcrop terminology. In subsurface geology, a detailed nomenclature is usually developed mostly for units having economic importance. Furthermore, the correlation of a particular rock unit in one area with that of another may be complicated by transitional changes in lithology. The unit may be a true limestone at one locale, elsewhere a dolomitic limestone, dolomite, or even a calcareous shale. Similarly, lithologic changes within the thickness of the unit itself produces added difficulties in recognizing its upper and lower boundaries (contacts).

The stratigraphic sequence does not necessarily imply continuous deposition. As sea level fluctuated, the shore line advanced or withdrew. Withdrawal of the sea from a region would result in the cessation of deposition, or more likely, the initiation of erosional processes which would alter or destroy part of the record. In either case, certain rock units would be missing and, if recognized, implies an interruption in the normal succession of stratigraphic units for that particular region. A readvance of the sea into the region would result in renewed deposition of sediments which then could take place on formations of different geologic ages. For example, in some parts of the state, the lower contact of the Sylvania Sandstone rests directly on Bois Blanc strata; elsewhere, it rests directly on other rock units that are progressively older than the Bois Blanc. Such a relationship is termed an unconformity. In summary, some rock contacts are sharply defined by lithologic changes, others are gradational, and some are marked by erosional intervals. The purpose of this discussion is to emphasize the difficulties involved in interpreting and correlating rock formations from one area to another.

If additional subsurface information is desired with respect to a project, the State Geological Survey in Lansing maintains a file of oil and gas well logs, a library of rock cuttings, and records of electric logs for many of the oil and gas wells drilled. The Survey also maintains a file of water well logs, most of which provide information as to the character of the materials that are found in the glacial overburden. Subsurface rock sample libraries are maintained by the major state universities. Other sources of geological information are listed in Michigan Geological Survey Circular 5 (Kelley and Kirkby, 1967).

Geologic Map

The bedrock geologic map (Plate 1) delineates the outcrop areas of the rock units present beneath the drift cover. Depending on the availability of information, some rock units shown consist of a single formation, whereas, others represent two or more. Because of the county's position along the southeast rim of the structural basin, the outcrop area of each rock unit occurs as a band of varying width crossing the region diagonally from northeast to southwest. The strata dip gently to the northwest at a rate of less than 50 feet per mile except where local structures cause steeper dips. A localized structure (rock flexure or possibly a fault) is suggested in Whiteford Township by the extreme narrowing of the individual outcrop areas and their abrupt change to a southward trend continuing into Ohio. The structure section A-A (fig. 18 centerspread) shows how rock units become progressively younger in the direction of dip. The pattern depicted on the large geologic map (Plate 1) compares favorably, in terms of gross features, with the small map (Martin, 1936) also reproduced as an inset on Plate 1. Note the changes in nomenclature. The Bass Islands Group in southeastern Michigan and northern Ohio was formerly subdivided, in descending order, into the Raisin River Dolomite, Put-in-Bay Dolomite, Tymochtee Shale, and Greenfield Dolomite. Today the two lowermost formations are often placed in the Salina Group in this part of the state.

The surface where two different rock units meet is termed a contact. Each contact represents the top of one unit or the bottom of the next higher one. Straight or gently curving contacts on a geologic map generally indicate a paucity of subsurface data and exposures. When numerous records and exposures are available, the added detail results in very uneven contacts. Sources for preparation of Plate 1 include: existing oil and gas logs, Sherzer (1900), Grabau and Sherzer (1910), Ehlers and others (1951), Martin and Straight (1956), and field observations. Formation contacts as drawn from these sources, were further modified in their details with respect to the configuration of the bedrock surface and through the evaluation of some 2500 water well records. Despite this effort, the density and distribution of control falls short of that desired for precise geologic mapping. Users of this map are reminded that contacts are inferred; rock units are concealed from direct observation over most of the area. Most geologic maps portraying hidden surfaces or features, especially in glaciated regions, are simply interim maps. Their accuracy increases as new data become available.

At places, the contacts project conspicuously northwest and west as in Milan and Whiteford townships. These projections coincide with the bedrock valleys (Plate 2). The patterns illustrate the "rule of V's" in which the configuration depends upon the angle and direction of dip of the formation and the slope angle of the bedrock surface. Those wishing to pursue this matter further will find adequate explanations and diagrams in any standard text on structural geology. The narrow outcrop widths, associated with the local structure in Whiteford Township, are a result of increased dip angle of the beds, and decreased thicknesses of individual rock units. The local structure extends southward into Ohio. This increased angle of dip, nearly due west, can be observed on all the north- and south-facing walls of quarries in the vicinity of Silica, Ohio. From here the thickness of rock units increases to the north and west. Steepness of the bedrock slope, assuming formation dip and thickness to be constant, is reflected in the much narrower outcrop widths appearing along the east-west rock valleys in Whiteford Township.

Other noteworthy features on the geologic map are the small isolated patches of one rock unit surrounded by another unit. When the isolated mass is enclosed by older (hence, underlying) strata the feature is called an outlier. When the isolated patch is older than the enclosing rock, the feature is called an inlier, or window, from which younger (overlying) strata have been eroded. The isolated rock knobs or upland tracts between rock valleys as in London, Dundee, and Whiteford townships (Plate 2) are outliers. An inlier is located near Azalia in Milan Township where ancient streams have cut completely through one rock unit thereby exposing, by way of a window, the underlying but geologically older unit. Another inlier occurs in Dundee Township about three miles northwest of the village of Petersburg.

Topography of Bedrock Surface

The present irregularities of the bedrock surface (Plate 2) were shaped both before, and during repeated episodes of Pleistocene ice advances. The bedrock surface of the Erie-Huron Lowland in Monroe County stands somewhat higher than Wayne County to the north (Mozola, 1969). The average elevation of the bedrock surface over much of Monroe County exceeds 600 feet above sea level. The highest elevation, 680 feet, occurs in Whiteford Township just north of Ottawa Lake village. The lowest elevation, 480 feet, is in the southeast corner of the county, in Erie Township. Thus, the southern part of the county has the greatest relief, approximately 220 feet.

The structure cross sections in figure 18 provide a picture of the regional slope of the bedrock surface. The northwest-southeast cross section (A-A), constructed perpendicular to the strike of the rock units, reveals a broad gentle swell through the middle of the county marked by a prominent rock valley along its northwest margin and by an abrupt change in slope along the Lake Erie side. The swell exhibits a gently undulating surface with a relief of 30-35 feet. The southwest-northeast cross section (B-B), constructed parallel to the strike of the rock units, reveals a rock surface steadily declining in elevation to the northeast; again, with a very modest degree of relief. The shallow trough developed over the outcrop area of Sylvania Sandstone suggests that formation is less resistant to erosion than the overlying and underlying carbonate rocks. Areas of stronger dissection, hence bolder relief, are present in the northwest, extreme west, and southeast.

Though the rock surface is highly dissected by valleys, the pattern does not appear normal. Two trends are noteworthy. One is represented by valleys having a northeast-southwest orientation which, in places, show a remarkable parallelism to the regional strike. This is well demonstrated by a prominent valley, paralleling the Traverse-Dundee contact, passing through Milan and Dundee townships; and by another valley in Whiteford and Summerfield townships. The contours also suggest that the westerly wall in both valleys is steeper than the eastern, a normal expectation for the existing geologic structure. Additional valleys of similar orientation but of much shallower depth can be discerned over much of the rock surface comprising the broad swell. These valleys could be the product of glacial erosion, or, perhaps, represent a series of poorly developed ice-marginal drainage channels resulting from the various positions taken by the ice front during the Wisconsin (the last) deglaciation (fig. 1).

The second trend is represented by valleys having a northwest-southeast orientation. At least two sets, in terms of age, may be distinguished. The older set is tributary to the prominent valleys just previously described in Milan, Dundee and Summerfield townships. The other set of similarly trending valleys is in the eastern part of the county and are perpendicular to the Lake Erie shore line. The upstream limit of these valleys appears to terminate near the Bass Islands-Salina contact. In all probability they are geologically younger than the other rock valleys of similar trend, and were carved in Late Wisconsin time when Lake Erie stood at a much lower level (perhaps corresponding in level to the low water stage of Lake Chippewa in the Lake Michigan basin and to Lake Stanley in the Lake Huron basin). During this time, the waters of the ancestral Great Lakes discharged through an outlet at North Bay, Ontario, thence to the Ottawa River and finally into the St. Lawrence Sea, now the St. Lawrence River (Hough, 1958, p. 295). Mapping of the rock topography beneath Lake Erie would substantially increase our knowledge of major pre-glacial drainage courses.

Limitations of the Bedrock Topography Map.

Mapping unseen irregular surfaces depends upon certain considerations. For example, detail shown is directly related to both the scale of the map and the number of points for which elevations have been obtained. The compilation of land surface relief maps is not encumbered by a limitation of control points because the surface being contoured is everywhere visible. This is not so for delineating the relief in a buried bedrock surface.

In preparing Plate 2 nearly 2500 bedrock elevations were plotted from soil test borings, water well logs, and oil and gas well records. The over-all coverage averages only about six control points per square mile--a rather meager number per unit area even if the distribution were uniform which, unfortunately, it is not. In most geologic mapping, data are seldom numerous and ideally distributed. On Plate 2, the contour lines are quite uneven in areas where control points are numerous (Bedford Twp.); and fairly straight or gently curving in areas where control is sparse (Ida Twp.).

The principal valley in Milan Township is fairly broad in contrast to its continuation in Dundee Township. This change in width may reflect the difference in control points between the two townships. Given additional new data for Milan Township, the interpretation might be revised to narrower valley with upland areas more highly dissected by first, second, and third order tributaries. On the basis of the existing records, the valley in Milan is between 70 and 90 feet deep. Conceivably, its depth could be greater because the present plotted elevations along the valley floor are not necessarily the lowest. Keeping these limitations in mind will insure the proper use and interpretation of this map.

Plate 2, despite the foregoing limitations, is important 1) as a base for increasing details of the bedrock surface by geophysical methods, 2) selecting underground routes for public utilities, thus minimizing cost of rock excavation by taking advantage of the existing rock valleys, 3) finding optimum foundation sites for heavy structures, and 4) locating buried rock valleys filled with permeable sands and gravels ideal for development of ground-water supplies.

Economic Resources

Sedimentary rocks are noted for containing nonmetallic resources as limestones and dolomites basic to basic industry. Unlike the metallic resources, most of the nonmetals have a high "place" value but a "low" unit value--most significant factors to an extractive industry concerned with supplying a nearby market. Too often the seeming abundance of these deposits elsewhere in the state tends to create a false impression regarding their availability. Actually, extraction and use depend greatly upon such factors as overburden thickness and chemical and physical quality. Also, ironically, the rapidly growing metropolitan area which creates the demand for these materials, forecloses their possible future when subdivisions cover a vital resource. A number of urban centers are now experiencing critical shortages of aggregate materials near enough to be economical in terms of transportation.

The drift cover in Monroe County is thinner than elsewhere in the southeastern Michigan metropolitan region. Development of bedrock resources, therefore, is favorable. Over three-fourths of the area has less than 50 feet of drift. Carbonate rocks are most abundant. Depending on their chemical and physical attributes, the uses for these materials are many. One is as fluxing agents in the making of iron and steel. Another potential is as crushed stone ranging from rip rap to crushed and sized aggregate for concrete. More effort should be made in testing, mapping, and researching these carbonate rocks to attract the attention of potential developers. Planning agencies, through appropriate zoning, should encourage the exploration and development of the bedrock resources by private enterprise. In some parts of the nation the shortage of high calcium limestone reserves, at or near the surface, is so acute that the stone is now extracted by underground mining.

Rock units having a special potential for economic development include the following: *Traverse Group*--high-calcium limestone for the cement, chemical, and agricultural industries; argillaceous limestone for cement making; shale for brick, tile, pottery, and, if characterized by good bloating characteristics, for lightweight aggregate production. *Dundee Limestone* and *Anderdon Formation*--for high-calcium limestone. *Detroit River Dolomite*--possibly for high magnesian dolomites for refractories. *Sylvania Sandstone*--for high purity quartz sand for glass, chemicals, and refractories.

The economic potential of rock units beneath the Salina Group appears to be restricted primarily to oil, gas, and natural brines. Though the Salina Group offers excellent possibilities for salt and artificial brine development by chemical industries elsewhere, this is not true for Monroe County due to the nearly complete absence of salt beds.

Currently some industries are interested in the possibility of disposing of liquid wastes into subsurface formations by deep well injection. A number of formations below the Salina Group offer possibilities but comprehensive geologic studies and testing are prerequisite. In any event, no formation immediately beneath the drift cover should be considered for disposal of waste--for reasons that should be obvious. Act 315 of The Public Acts of 1969 (Michigan) provides for state regulating control of underground disposal of wastes, and inquiries regarding this activity should be addressed to the Supervisor of Mineral Wells, Geological Survey Division, Michigan Department of Natural Resources.

Carbonate rocks are relatively soluble. Hence, bedding planes, joint systems, and fractures tend to be further enlarged by circulating waters often becoming subterranean passageways. When the roof of such an underground passage collapses, the depression thus created on the earth's surface is called a sinkhole. Sherzer (1900, p. 214-219) discusses sinkholes in Monroe County, the most prominent are shown on Plate 1. Several others have been uncovered in the course of overburden stripping operations in quarries but have been destroyed. Other sinks may be present beneath the drift as suggested by low bedrock surface elevations not related to rock valleys.

Though subterranean openings on a minor scale do exist, their delineation and degree of development are not fully known. Their presence is sometimes suggested in oil, gas, and water well records by such notations as open fissures, cavernous rock, water seams, brecciation, voids, and caving of rock during drilling. Such subterranean passageways function as conduits for ground-water movement. Hence, unexpected and copious volumes of water can be encountered during quarry development or in deep excavations of any kind. The same solutional features, considered detrimental to excavation and quarry development projects, become favorable features for ground-water development.

Ground water associated with carbonate rocks is often impaired by hydrogen sulfide recognized by its disagreeable odor. In sufficient quantity, it hinders quarry development because such water cannot be discharged directly into surface streams without prior treatment. Its toxicity also constitutes a lethal hazard to personnel required to work in cuts, trenches, caissons, or other poorly ventilated excavations.

Summary.

The bedrock formations in Monroe County are a potential source of industrial minerals ever demanded in a metropolitan area. In assessing the significance of these resources, the following characteristics are most significant: 1) their location is fixed, thereby creating a "high" place value, 2) their usually "low" unit value makes them sensitive to transportation costs, 3) their quantity is limited by accessibility and quality factors, and 4) they are not renewable. The cost of industrial minerals will begin to rise sharply as transport distances become greater. Increasing costs, however, might be alleviated to some extent by new legislation pertaining to the planning, zoning, taxation, and development of known and potential sources of construction materials. Finally, one of the foremost prerequisites is mapping and inventorying the bedrock resources on the basis of their economic potential.

GLACIAL GEOLOGY

Nature of Deposits

The unconsolidated rock material covering the bedrock surface throughout Michigan is termed "drift". It is recognized by its heterogeneity of grain size and mineral composition. Drift may have been deposited directly by the glacier, or, indirectly, by melt water discharging from the ice mass. Direct deposition by ice results in unsorted deposits usually rich in clay or clay admixed with varying a-mounts of coarser particles ranging from silt to boulders. *Till* is debris of this description, and is the dominant material of moraines (fig. 2). End moraines are irregular hilly belts, or ridges. They are not present in Monroe County, but appear as prominent landscape features to the west and northwest in Lenawee and Washtenaw counties. Till plains, also known as ground moraines, are essentially flat to gently undulating terrain. In Monroe County a till plain, perhaps, in part a subdued waterlaid end moraine, is presumed to overly much of the bedrock surface.

Materials laid down by the action of glacial melt water results in deposits that are sorted, stratified, often crossbedded, and usually low in the clay-silt-size fractions. Landscape features include *outwash plains, marginal outwash, glacial spillways, eskers, kames,* and *kame terraces* (Martin, 1955). The magnitude of these melt water features may be great or small. Collectively these are classified as glaciofluvial deposits and, in terms of ground-water transmission, are more favorable for developing water supplies. Rarely is till entirely devoid of water-sorted sediments, or glaciofluvial features completely free of till. The following points should be considered: 1) an active glacier performs both erosional and depositional work producing debris and subsequent landscape features in which both till and glaciofluvial materials are represented, 2) although the ice front fluctuates, it halts occasionally to build end moraines, 3) melt water volume may fluctuate greatly in response to climatic changes, as indicated by the amount and kind of sediments, 4) the ratio of till to glaciofluvial sediments is normally greater during the advancing (cooler climate?) phase of a given glacial episode; the ratio decreases during retreat in response to a warming climatic trend, and finally 5) Michigan has experienced several episodes of glaciation, each separated by a warmer interglacial period during which the material already deposited was partly reworked, eroded, and weathered.

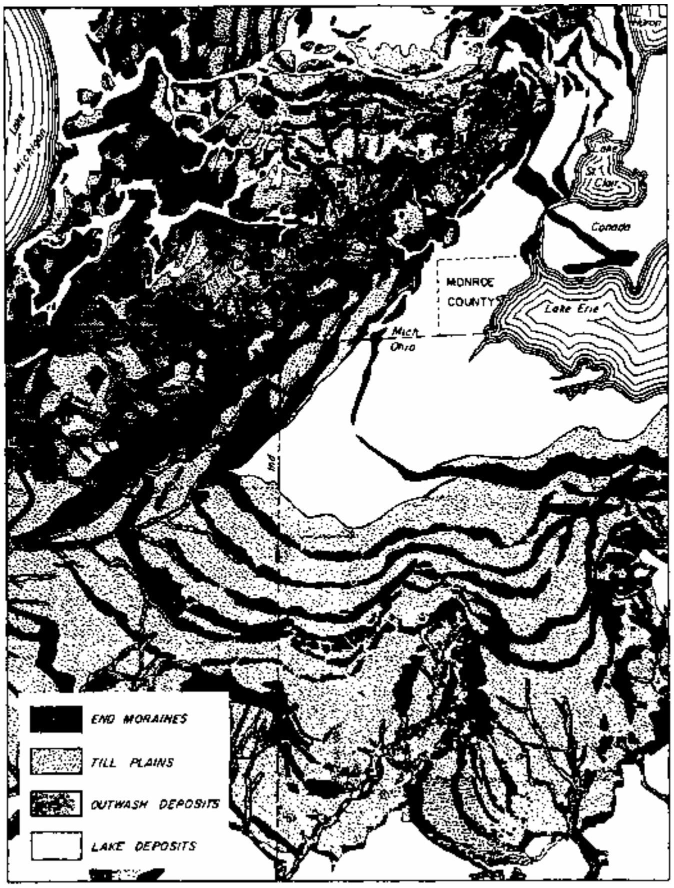

Figure 2. Glacial features of southern Michigan, northwest Ohio, and northeast Indiana (after Geological Society of America, 1959).

The range of composition and grain size of glacial drift is indeed broad. One end is represented by the less permeable clay-rich admixtures known as till; the other end by the more permeable materials of glaciofluvial origin. Between these extremes are many possible gradations with sharp contacts between till and glaciofluvial materials the exception rather than the rule. For a comprehensive description and interpretation of these materials and the features they form the reader is referred to Flint (1957). In Monroe County, glaciofluvial deposits are absent on the surface but present sporadically as included bodies of various dimensions within the till.

A glacier moving over a dissected rock surface completely disrupts the former drainage--streams are impounded, drainage is reversed, lakes are created. Associated with the latter are glaciolacustrine features such as beaches, shore lines, bars, deltas, as well as sandy, silty, and/or clayey lake bottom deposits. Behind the shore lines, prevailing winds build dunes from the beach sands. The glacial geology of southeastern Michigan is described in detail by Leverett and Taylor (1915), Sherzer (1900, 1916), Stanley (1936), Bay (1938), Berquist and MacLachlan (1951), Hough (1958), and Wayne and Zumberge (1956).

Drift Thickness Map

In Monroe County, the drift cover (Plate 3) varies in thickness from a few inches to more than 150 feet. Drift less than 50 feet thick occurs mainly over the broad bedrock rise trending northeast-southwest across the county. Where the drift exceeds 50 feet it is associated with well defined valleys carved in the rock surface, particularly in the southeastern, western, and northwestern townships. Though the present surface of the county is essentially flat, the thickness of the drift is not uniform. It is irregular, and reflects the topography of the bedrock surface. This relationship becomes quite evident when the drift thickness map is shaded at 40-foot intervals.

The same well and test boring data were used in compiling the drift thickness map. Inasmuch as the number and distribution of many drift thickness values were less than ideal, estimated thickness values (one per 160-acre tract) were determined and plotted. These estimated values represent the difference between the bedrock and ground surface elevations. This procedure was necessary so that the trends exhibited by the thickness contours conform to the bedrock surface topography. This procedure should be taken into consideration when making interpretations from this map.

On the basis of a number of schematic cross sections (Plate 4), the bedrock surface appears nearly everywhere to be overlain by unstratified stiff, blue-gray clay admixed with varying proportions of silt, sand, pebbles, and cobbles. This clay admixture is till, deposited principally as a till plain, the uppermost portion perhaps somewhat modified or reworked by ancestral lakes. In some areas the till contains an extremely high percentage of small stones difficult to penetrate with the drill. This compacted stony till is usually called "hardpan" by drillers. However, it is not consistent throughout the county. In places, the till is exceptionally sandy indicating the influence of the friable Sylvania Sandstone. In the schematic cross sections, sand lenses occur anywhere within the total thickness of the till; at times, along the bedrock surface at widely scattered localities and occasionally, along the floor of rock valleys. These bodies are not exceptionally large or continuous. Gravel is quite rare and is found associated with the sand lenses or as pebbles contained in the till. The cobbles and boulders present in the till matrix are igneous, metamorphic, and sedimentary with the latter predominating. Because the local bedrock is mostly limestone and dolomite, the pebbles and cobbles within the till are largely that composition. Extremely large boulders, termed erratics, are present within the drift and, in drilling, may be mistaken on occasions for the bedrock floor. Although the till is generally blue to blue-gray, its color changes to a mottled reddish-blue gray, thence to a dominantly red or brown as the surface is approached. Thus, the till near the surface has been oxidized through weathering. The depth of discoloration varies from place to place depending upon topography and drainage. Generally it varies between 1 to 3 feet in depth but, in some instances, the discoloration extends to depths of 14 to 16 feet before the blue-gray unweathered till is reached.

The Erie-Huron Lowland surface, of which Monroe County is but a small part, coincides with the glacial lake plain region of southeastern Michigan. This lake plain, representing a series of lake stages ancestral to our present Great Lakes system, is recognized by the presence of lacustrine clays, silts, and sands, now covering the till plain along with several, but poorly defined, waterlaid end moraines. The succession of the various lake stages, as indicated by remnants of several shore lines in southeastern Michigan, is treated in detail by Hough (1958) and summarized by Kelley and Farrand (1967). The waters of the various lake stages were impounded between the topographically higher end moraine systems to the northwest, southwest, and south, and the gradually shrinking Erie-Huron ice lobe (fig. 2). With development of the first lake stage, the materials deposited initially by the glacier were undoubtedly subjected to reworking by the lake waters. Streams originating in the adjacent deglaciated and higher morainic tracts to the northwest (Thumb Upland Surface) discharged into the early lake.

Summary. The earlier deposited till is nearly everywhere thinly veneered by lacustrine deposits except for recent alluvium found along the major stream valleys, and the recent deposits fringing the Lake Erie shore line. The areal distribution of these surface deposits is shown on the glacial map of the county (Plate 5) compiled after the work of W. H. Sherzer (1900) and modified or corrected on the basis of records of water wells drilled between 1961 and 1967.

GROUND-WATER RESOURCES

Except for the cities of Monroe and Dundee, which obtain their water supplies from Lake Erie and the Raisin River, the county depends on wells for water supply. Municipal well systems serve the towns of Carleton and Petersburg; elsewhere individual households depend mainly on domestic wells. Occasionally, subdivisions have community wells. Of the 2300 water well records collected for this study, nearly 2100 wells, or 90 percent, are completed in bedrock; the remaining 10 percent are completed in sand and gravel deposits in the drift. Wells completed in confined sands and gravels are generally located in areas underlain by thicker drift. Depth of these wells is determined by the depth at which water-bearing sand and gravel horizons are encountered. Though these aquifers could be of any shape, magnitude, and depth, (see Plate 4) they do not occur frequently in Monroe County because of the generally thin drift. Shallow dug or driven wells are not numerous despite the presence of extensive tracts of lacustrine or deltaic sand. The scarcity of this type of well implies an uncertain yield due to the limited storage capacity of these surface sands, prolonged periods of droughts, and/or a decline of the water table.

Porosity and Permeability

Porosity is defined as the volume, usually expressed in percent, of unoccupied space present in sediments or bedrock. With rare exceptions, most materials at or near the earth's surface possess some degree of porosity. Porosity may be primary or secondary; the former are interstitial voids between individual grains, while the latter are all other openings that develop at some later time as joints, fractures, and solution channels. When the various openings are interconnected with each other an "effective" porosity develops. The unconsolidated glacial sediments of Monroe County are dominantly characterized by a primary porosity, whereas, the sedimentary strata possess a secondary porosity in addition to their inherent primary openings. Hydrologically, porosity is important because it permits storage of water in the subsurface and, when determined quantitatively, it represents the storage coefficient for a given material.

Permeability is the ease with which water may move through the openings of a given medium. Its quantitative determination represents the materials coefficient of transmissibility. It also can be considered as the frictional resistance the medium offers to the passage of water. Porosity is a requisite of permeability. On the other hand high porosity does not guarantee high permeability. For example, clays have high porosities but are considerably less permeable than most sands and gravels whose porosities may be appreciably less. However, larger-sized particles result in larger openings, a smaller total surface area, and, hence, less frictional resistance. Shales in contrast to sandstones, limestones, and dolomites, are frequently less permeable. In Monroe County the permeability of the glacial sediments is essentially an attribute of primary porosity; whereas in the bedrock, the permeability is determined by the primary and secondary openings. Movement of water through the shale formations of the Traverse Group may occur largely along the principal fractures and joint patterns with very little passage through the primary openings. In this case, a permeability due to secondary porosity prevails. For the weakly cemented Sylvania Sandstone, the movement may be largely through the interstices between grains, rather than along joints and fractures, hence a primary permeability would dominate. Carbonate rocks, by virtue of their solubility, are characterized by a permeability that improves with time; the bedding planes, fractures, and joint patterns are progressively enlarged by solution thereby increasing their effectiveness as conduits. Since carbonate rocks dominate in Monroe County, their potential for ground-water development can be considered favorable. For the same reason, copious ground-water flows could be encountered in excavation projects extending down into these carbonate rocks.

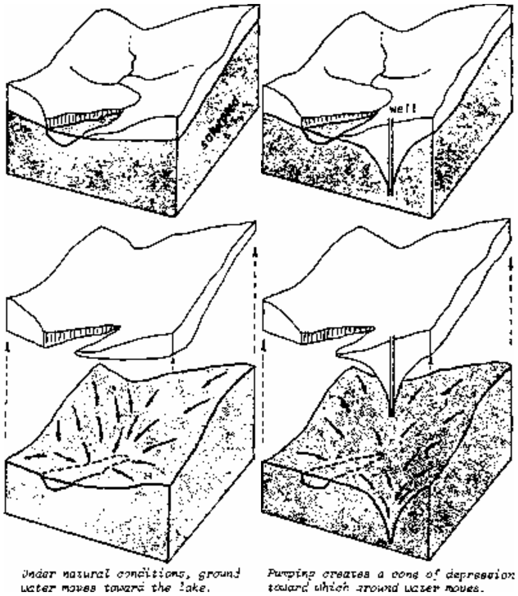

Figure 3. In general, the water-table surface is a subdued reflection of the overlying land surface (after U.S. Geological Survey, Primer on Water).

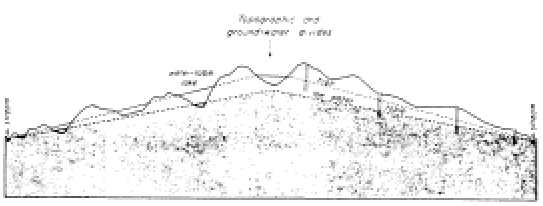

Figure 4. The water levels of lakes and wells respond to fluctuations of the water-table surface.

Porosity and permeability relationships of materials are not only important to the movement of water within the ground-water environment, but also to the entry of precipitation into the subsurface. Though the infiltration of water may be only a fraction of the total precipitation, the quantity stored becomes significant over a broad area of rainfall. Finally, inasmuch as few naturally occurring materials are homogeneous throughout their thickness and breadth, movement of water in the subsurface environment is very complex.

Water Table

At some depth below the surface, materials become saturated with water; the lowermost limit of saturation is determined by the absence of voids and other openings. The upper surface of this saturated zone is called the water table. It demarks the saturated ground-water zone from the overlying unsaturated vadose zone. The surface of the water table is not a smooth plane but highly irregular. Its configuration, if it could be seen, is a subdued replica of the irregularities of the land surface (fig. 3). Both topographic and hydrologic features influence the configuration of the water-table surface. The water table is not static but dynamic; it rises and falls in response to conditions of precipitation. A decline in the water table increases the thickness of the vadose zone (fig. 4) which, in some instances, might seem unfavorable. From a hydrologic viewpoint this condition allows for more storage of water during the next wet period thereby minimizing the intensity of stream flooding. A more complete saturation of the vadose zone leads to increased runoff and, as a consequence, more severe stream flooding.

Figure 4 illustrates two basic concepts: the depth of the water table at any point is largely a matter of local topography, and, the amount of water-table fluctuation for the wells and lakes depends mainly on their position within the drainage basin. Fluctuation is greatest at divides, and diminishes towards stream outlets. Hence, during a period of prolonged drought, lakes and wells situated in the lower reaches of a drainage basin maintain their levels while lakes and wells located higher in the same drainage basin undergo notable declines.

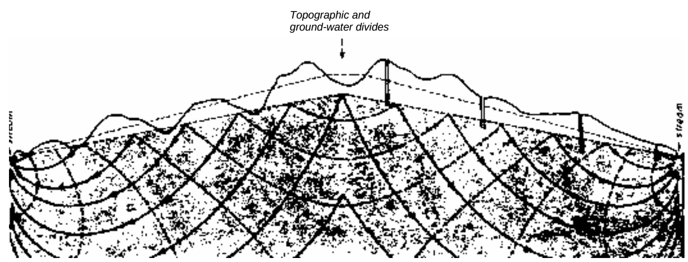

Figure 5. In a theoretic model of an isotropic aquifer, ground water moves in the direction of diminishing head. Dashed lines connect points of equal head.

Occurrence in Drift

Water-Table (or Unconfined) Aquifers

Water seeks its own level. In figure 5 the subsurface materials are assumed to have uniform physical properties, hence, an isotropic medium. Because stream valleys function as discharge outlets, the resulting slope of the water table indicates not only the head available for ground-water movement but, also, the direction towards which it is moving. The path taken by an individual water molecule is a compromise between gravity and the available head represented by the water-table gradient. Therefore, ground water in an isotropic medium moves along curved paths; the lines of flow originating at the water table, move downward below the level of saturation for some distance and, thence, upward towards the outlet. Along these lines of flow a progressive loss of head occurs in the direction of the outlet. This loss also can be represented by another set of curved lines, called equipotential lines, connecting points of equal head. Any number of flow and equipotential lines can be drawn for a flow system, but a finite number adequately portrays the flow and distribution of head.

In the movement of water through a porous medium, energy is consumed in overcoming the frictional resistance of the material. The energy for this movement is derived from the difference in head between the discharge and intake areas. Movement is downward where the head decreases with depth; and upward when the head increases with depth. Even in the most isotropic (structureless) medium, the head, at some depth in the discharge area, will be higher than the water table; and lower, in a recharge area. Thus, a well in the stream channel completed at some depth will have a water level standing higher than the level of the stream itself. This increase in head potential with depth in the discharge area can be verified by drilling wells of different depths in the stream channel. It will be found that the deepest well will have the highest level. Conversely, wells completed to some depth in the recharge area (region of the ground-water divide) will have water levels lower than the water table. The flow pattern and distribution of head in an isotropic medium are demonstrated by laboratory ground-water models (Harshbarger et al, 1963).

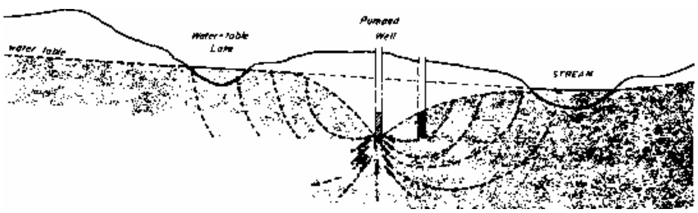

Figure 6. The cone of depression resulting when a water-table well is pumped may affect nearby wells, lakes, and streams.

Surface sand and/or gravels that are isotropic, or nearly so, comprise water-table or unconfined, aquifers. The wells shown in figure 6 are classed as water-table wells. If penetration below the water table is shallow, the water level of each well should nearly match the level of saturation of the sediments surrounding the well. When a water-table well is in operation, water is withdrawn from the aquifer in excess of the natural rate of movement through the material. The saturated sediments in proximity to the well are immediately de-watered thereby initiating the development of a "*cone of depression*", steepening the hydraulic gradient around the well so that movement of water into the well balances the amount of water being withdrawn. Although the cone, after some period of pumping, may appear to be in equilibrium, it expands very slowly with continued pumping, providing the withdrawal rate does not exceed the aquifer's coefficient of transmissibility. A well in operation serves as an effective discharge outlet; hence, the natural flow pattern becomes modified in the vicinity of the well. In figure 6, the cone developed by the pumped well has affected the water level of a nearby well and lake. Continued expansion of this cone to intercept the stream channel can lead to the steady state condition whereby ground-water discharge from the well is balanced by recharge into the aquifer. Cessation of pumping results in the disappearance of the cone and a nearly complete recovery of the water table to its original level and gradient.

Whenever depth-to-water-table data are sufficiently abundant in a given area, a contour map of the water-table surface may be prepared by a ground-water hydrologist. Such a map is useful because it depicts the irregularities of the water-table surface, assists in distinguishing between intake and recharge areas, and reveals the direction of movement of the ground water. Though the water-table map (fig. 7) shows a regional movement of ground water to the southeast for most of the area, the movement for a particular locality may be in a totally different direction. The details of movement are not simple but complex as shown by the use of small arrows drawn at right angles to the water-table contours. These arrows, point in the direction of steepest hydraulic gradient and, therefore, the many directions towards which water is moving. They are not intended to imply that ground-water movement is horizontal. Hydraulic gradients are three-dimensional and a quick reference to the flow diagram in figure 5 will remind the reader that movement of water molecules is not only horizontal along the water table but also downward below the water table in the recharge area, and then upward in the discharge area. Unfortunately, contour maps of the water table are not available for most areas, or, if available, are extremely generalized due to the paucity of data. However, theoretical water-table maps may be prepared for some areas by using surface hydrologic and topographic features (Mozola, 1966).

Despite the extensive tracts of surface sands in several townships, shallow water-table wells are conspicuously few. These deposits, generally resting on till, are relatively thin and, perhaps, for the most part occur above the water table. Hence, water-table wells in these sands are possible only where their depth and breadth are sufficient for local perched water-table conditions, or where they extend in depth to the bedrock surface and, therefore, affected by the artesian occurrence of ground water found in the bedrock aquifers (fig. 8). For the conditions as shown the pumping of water-table wells can induce flow from the underlying rock formations into the sand aquifer. Conversely, the withdrawal of water from the bedrock aquifers results in an opposite movement. During spring thaws and periods of excessive precipitation, these tracts of sand function as recharge areas for the bedrock aquifers.

Artesian (or Confined) Aquifers

Unconsolidated sediments of whatever origin are seldom structureless (completely isotropic) over a large area. Instead they are characterized by changing lithologies affecting their porosities from place to place, and their permeabilities. For example, the inclusion of two clay horizons in a glacial outwash deposit (fig. 9, right side), not only distorts the original flow lines, but also channels some flow between the clay-till layers, introducing some degree of ground-water confinement. As clay-rich materials become more and more dominant over the permeable sands and gravels, as in morainic landscapes, greater confining conditions result. Furthermore, where the permeable and confined materials are irregular or distorted, the movement of ground water toward some effective discharge area must follow an irregular path. Whatever path the water may take due to changing lithologies, it is still the course of least resistance or most efficient in terms of head expended. Extreme differences in permeability as just described are not absolutely essential in an artesian system. When present, and extending over a wide area, such conditions produce larger, more effective, and predictable artesian systems.

Local artesian structures can, and do, exist within thick and extensive surface aquifers. The coarse sand and gravel horizon shown in figure 9 (left side) functions as an artesian aquifer by virtue of a more favorable transmissibility in contrast to the enclosing finer sandy sediments.

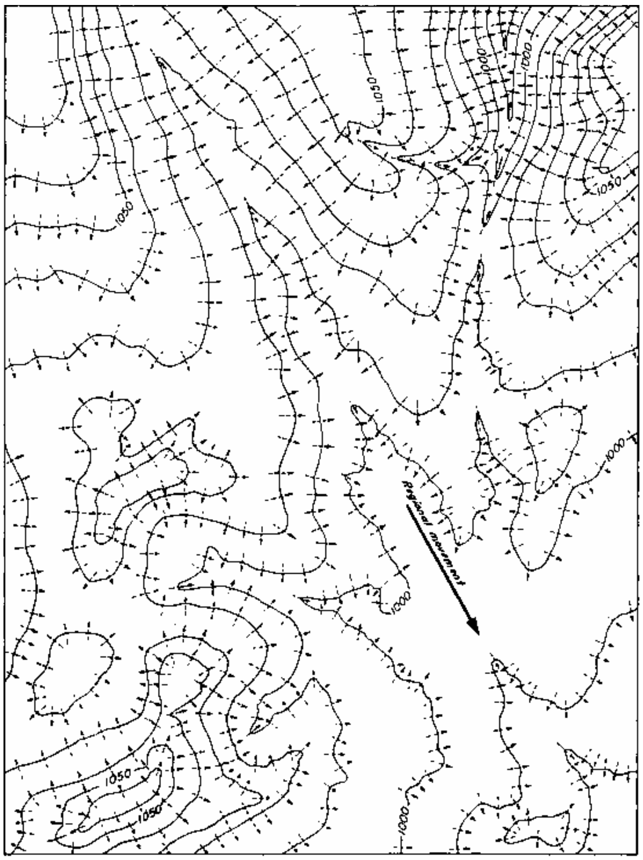

Figure 7. This hypothetic water-table contour map shows how local ground-water movement may vary considerably from the regional movement.

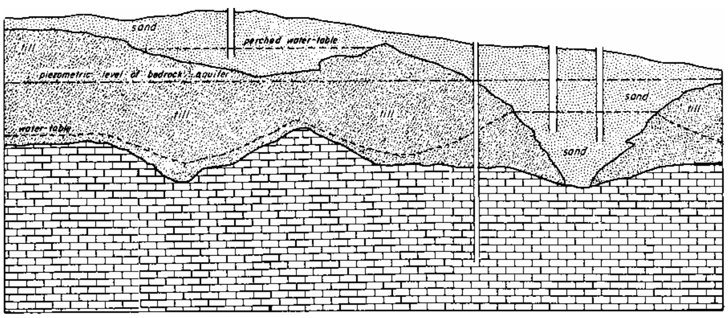

Figure 8. Perched (false) water tables are not uncommon in glacial deposits.

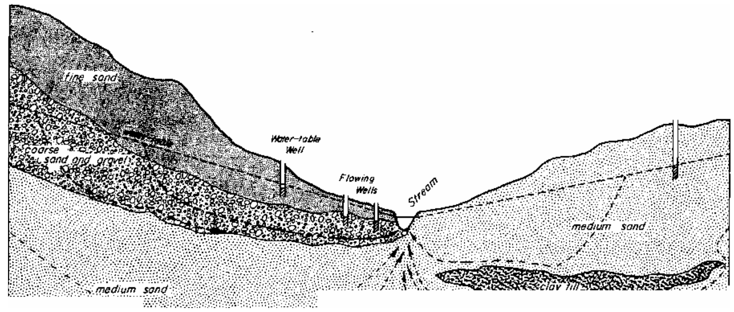

Figure 9. Changes in glacial drift lithology often result in confined conditions of ground-water movement.

In glacial terrane, the surface sands and/or gravel bodies of whatever origin, constitute essentially water-table, or unconfined, aquifers provided their lower portions are saturated. Sand and/or gravel deposits completely, or partly, enclosed by less permeable materials constitute the confined aquifers, and represent many small and somewhat imperfectly developed artesian systems in the drift. Fig. 10 schematically represents unconfined and confined aquifers occurring within the glacial lake deposits of southeast Michigan. In cross section the aquifers appear rather restricted and ineffective to develop ground-water supplies, or, to cause problems in deep excavations. This applies when attention is simply focused on the geologic and hydrologic conditions of the particular site.

A different idea emerges, however, when the site is studied with respect to the surrounding terrain. Figure 11 shows the distribution of sand and gravel deposits as they appear on the surface today in southeast Michigan. Between and beneath these sandy deposits are layers of till and lacustrine clays of poor transmissibility. This plan view reveals that most of the unconfined surface aquifers are interconnected rather than isolated bodies, and that their elevations increase northwest towards the topographic divide as indicated by the elevations. This topographic divide not only marks the approximate axis of the Interlobate Moraine but also roughly coincides with the divide of the Thumb Upland bedrock surface (fig. 1) and the water-table divide. Thus, both surface and subsurface waters drain northwest and southeast from the divide.

A confined condition results whenever permeable surface deposits as shown in fig. 11 are buried by till. Hence, this system of interconnected drift aquifers then becomes comparable to a municipal water system consisting of distribution mains and laterals. Unlike the municipal system, the artesian system is imperfect because it consists of highly irregular "conduits" and lacks booster stations and gate valves to control the pressure, volume, velocity, and direction of water flow. Determination of these values for any point in a natural artesian system is difficult, and, when obtained, the values cannot be used to interpolate between known points with a high degree of confidence. Though this system of confined aquifers may be quite imperfect, it is not necessarily small. For this buried aquifer network, the major intake area must lie along the topographic divide; and the difference in elevation between the water-table divide and the surface of Lake Erie provides the system with the energy to move the ground water.

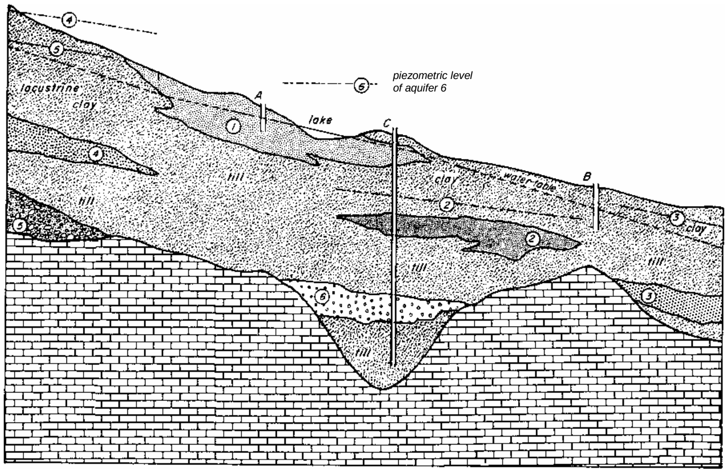

Figure 10. Diagrammatic cross section showing five different confined aquifers and their corresponding piezometric levels.

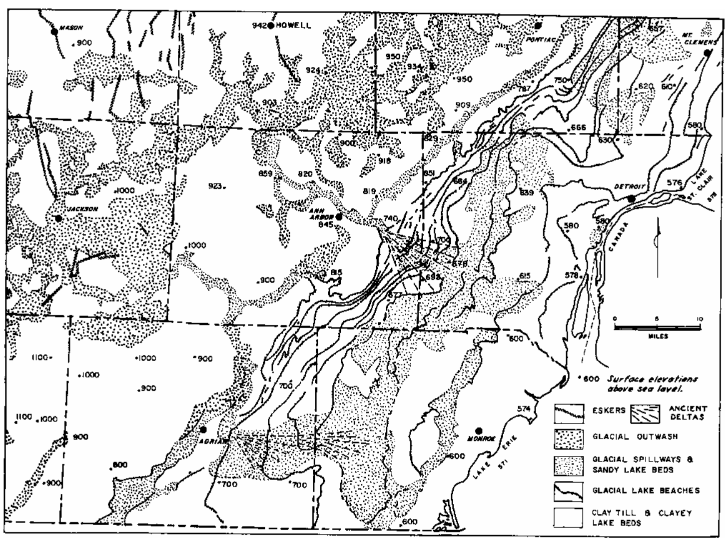

Figure 11. Distribution of sandy and gravelly surface features in southeast Michigan.

Though glacial drift can consist of a variation of glacial, glaciofluvial, glaciolacustrine, and glacioeolian lithologies, the permeability of these materials is relative, and not simply pervious or impervious. A large cross section of clay-rich till can pass as much water as a small cross section of sand. A body of sand and gravel completely enclosed by a water-saturated till of low permeability can still function as a good aquifer because of extensive contact with till. Even if the till is capable of transmitting only one cubic centimeter of water per square inch per day at its contact with the sand and gravel, the till would transmit more than one million gallons daily per square mile of contact. All the aquifers and surrounding matrix are water-saturated if they occur below the water table. Therefore, the withdrawal of water from a deeply confined aquifer creates a greater water pressure differential between aquifer and matrix in contrast to one at a shallower depth below the water-table surface. Thus a confined aquifer, or aquifer system, can also be recharged by crossbed leakage.

The following comments pertaining to fig. 10 summarize hydrologic principles:

1) Heavy withdrawal from surface aquifers as at site A produces immediate effects on surface water bodies. These effects normally show up in pump tests of short duration. Response of surface water bodies and the water table to heavy withdrawal from confined aquifers can be slow and unnoticed. With deeper aquifers, longer observation periods are necessary to detect responses, but this may not always be feasible in terms of costs involved.

2) Each aquifer has a different lithology, hence, a different resistance to passage of water. For the confined aquifers shown, the piezometric level may be above the ground surface, somewhere within the un-saturated vadose zone, or somewhere below the water table. Changes in lithology within an aquifer also result in variations in permeability. Thus, the piezometric levels for each of the aquifers illustrated are not smooth inclined planes, but are actually irregular and uneven surfaces.

3) Well "B" completed in water-saturated till or lacustrine clay would yield so little water it is practically a dry hole. A test hole at site "C" would result in different water levels as the different aquifers were penetrated. This situation indicates the difficulty in compiling piezometric water-level and water-table maps for glacial drift.

4) A deep cut into glacial drift could intersect surface and/or confined aquifers. Even though no serious water seepage problem develops at the site, nearby domestic or subdivision wells may subsequently fail or be reduced in performance. In areas of shallower drift, a similar cut may encounter a confined aquifer closely related to a bedrock aquifer thereby creating a water problem at the construction site. Both these water problems have occurred during expressway construction in southeastern Michigan.

In Monroe County, recovery of ground water from confined aquifers of glacial origin is primarily limited to areas where drift overlies valleys previously carved in the bedrock surface (plates 2 and 3). At such sites the drift may range in thickness from 50 to 160 feet or more. There is no assurance that the drift within, and lying above, the rock valleys will always contain bodies of sand and gravel of sufficient magnitude to function as aquifers. Nor can they be predicted without recourse to test drilling or geophysical surveys. Increased drift thickness, however, increases the probability of a suitable aquifer, or even aquifers.

Occurrence in Bedrock

Many crystalline rocks of igneous and metamorphic origin have extremely low primary porosities and, hence, ineffective primary permeabilities. Movement of ground water through such rocks is essentially along joints and fractures which represent a secondary permeability. Crystalline terranes, perhaps more than any other, exhibit confined ground-water movement at its best, providing frequent recharge by precipitation takes place to offset the limited storage capacity of such rocks.

Sedimentary rocks, on the other hand, are characterized by two kinds of permeability: 1) an intersecting system of joints, fractures and bedding planes, and 2) primary porosity. Hence, depending upon the amount and kinds of sedimentary strata present in a region, ground water may move mostly through either type or a combination of both. Due to their relative solubility, carbonate rocks become more permeable as the secondary openings are progressively enlarged.

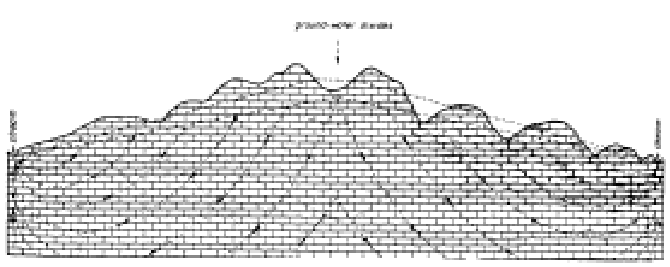

Figure 12. In carbonate rock terrane, ground-water movement can be unconfined if uniform primary permeability dominates, but as solution channels develop in the soluble rocks a confined water movement develops.

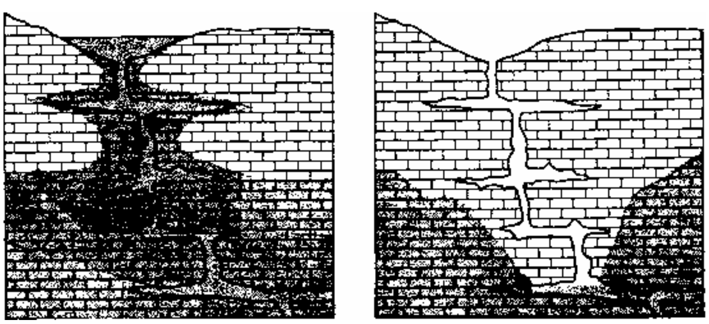

Figure 13. An effective primary porosity in carbonate rocks results in added ground-water storage.

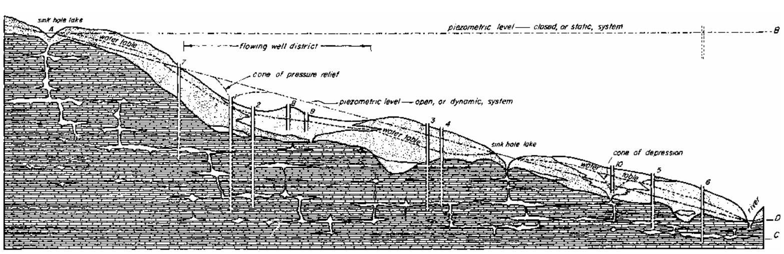

Figure 14. Piezometric level and water table are parts of a single hydrologic system.

Circulation

Assuming a carbonate rock sequence has a uniform primary permeability that dominates a secondary permeability, then the ground water will circulate in an arcuate pattern (fig. 5). The joints, fractures, and bedding generally present in carbonate rocks are enlarged by solution. Consequently, the lines of flow will be gradually modified. As these openings are progressively enlarged more and more confined movement of ground water develops (fig. 12). These solution-enlarged openings, or subterranean channelways, are completely saturated if they occur below the water table. If above, they may be dry or partly filled but, nevertheless, serve as conduits for the drainage of surface water to the water table. In instances, the channelways above the water table may develop a subterranean drainage pattern somewhat comparable to a surface drainage pattern present in regions underlain by less permeable material.

Owing to the diversity of geologic conditions, amount of precipitation, and the physiographic development of the subterranean caverns, the water table in carbonate terrane is difficult to define. In fact, water-table conditions may be so abnormal as to defy description or the mapping of its surface. Some investigators even abandon the usual concept of a water table. This uncertainty regarding the existence of a water table is caused by the pronounced difference in permeability between the primary and the enlarged secondary openings and, to some extent, by lithologic changes in the stratigraphic sequence. The subterranean channels represent considerable larger openings, in contrast to the primary pores which may, or may not, be interconnected. Thus they are prone to rapid recharge during precipitation but, by the same token, they also lose water rapidly in the intervals between precipitation. Movement of ground water through primary openings in the carbonate rocks depends, in part, upon the pressure differentials created (fig. 13). Shale horizons in the carbon ate sequence further complicate the behavior of ground water by creating false, or perched, water-table conditions. Unless primary porosity in carbonate rocks is almost completely absent, the idea that a water table cannot exist at some depth is difficult to accept.

The depths to which subterranean channels may develop by solution below the water table is a debatable issue. Carbon dioxide (CO2) contained in ground water, increases the solvent action of water on carbonate rocks. Other factors, such as climate, degree of solubility of the limestones and dolomites, and amount of time, are also significant in cavern development. The consensus appears to be that most active solution of the carbonate rocks takes place in the uppermost portion of the zone of saturation because of shorter and more direct flow lines to the discharge areas, greater circulation, and ground, water is not completely saturated with salts at shallower depths. The greater solutional activity in the uppermost part of the saturated zone results not only in progressively larger subterranean conduits but, at the same time, brings about a gradual decrease in both the flow of water and the rate of solution at deeper and deeper levels. However, the vertical range of cavern development can be increased by lowering the water table. Fig. 5 shows how streams function as local base levels controlling the water table. As the stream cuts deeper in its valley, the water table is also lowered until the stream reaches a graded, or stabilized, condition where the valley is no longer deepened. In Monroe County the streams attained base levels during the low water stage of the ancestral glacial lake that occupied the Lake Erie basin. This is strongly suggested by several well defined bedrock valleys perpendicular to the present shore line of Lake Erie (Plate 2).

Subterranean channels are not developed extensively in the county. Several sinkholes in Whiteford, Bedford, and Ida townships, however, indicate the possible occurrence of underground channels. Others were uncovered at quarry sites (Sherzer, 1900). Doubtless other shallow sinks are concealed beneath the drift having been buried by Wisconsin till and lacustrine sediments. Large artesian springs (as reported by Sherzer) suggest cavernous conditions. Located mainly along the eastern margin of the county these springs were usually characterized by strong odor and taste of sulfur. Sherzer also noted an opening "large as a room, 12 to 14 feet" at the foot of the Ottawa Lake sink. Other bits of evidence suggesting subterranean channels are the references to the use of old wells for draining farm lands, the annual appearance and disappearance of sink hole lakes (Big Sink and Ottawa Lake) and, on occasions, the loss of an entire water supply in a well during deepening. Notations relative to open crevices, brecciation, rock cavings, and "water seams" are not uncommon on driller's logs.

Piezometric Levels

Figure 14 shows confined and unconfined conditions of ground-water occurrence and also aids in differentiating the piezometric water level from the water table. The underlying carbonate formations are assumed to have both primary and secondary permeability, the latter predominating. The rock surface, in turn, is covered essentially by a clay-rich till of low permeability but containing occasional bodies of sand and gravel functioning as aquifers. Ground water in the carbonate formations is under confined conditions regardless of whether it occurs in the pore spaces or in the solution enlarged openings.

Water in a U-shaped tube comes to rest at the same level in both sides. A structure, analogous to a U-shaped tube, can be traced from the sinkhole lake situated high on the divide, through the solution-formed passageways in the carbonate beds, thence into well #6, and finally upward to point B. The double dotted line represents well casing extended above the ground surface. Assuming for the moment that this U-shaped structure is a closed, watertight and frictionless system, the height of the water level in well #6 should correspond to the level of the lake. The line A-B is the water-pressure, or piezometric, surface for this structure, not the water table. The total head, or energy available for movement of water through the structure, is represented by B-C, the highest and lowest water elevations in the confined system. Under natural conditions, static, watertight, and closed systems are rare because water in a confined system is usually moving and, in time, discharges at some outlet or outlets with a resulting loss in head. Further losses in head result from leakage of water into the confining materials, and in overcoming the frictional resistance of the passageways. These combined losses are equal to line B-D; hence, A-D now represents the existing piezometric surface for this U-shaped structure. Again, this is a pressure surface -- not a water table -- indicating the height to which water in the subterranean passageway would rise in a well for the particular site selected. Though diagrammed as a flat sloping plane, this surface is highly irregular in nature. Head loss is not uniformly distributed because the channel network is in three dimensions. Though the piezometric surface is irregular, it slopes towards the effective discharge outlet represented by the stream.

In considering the piezometric level in relation to both the ground surface and the water table, the following conclusions are drawn from the diagram:

1) Any well that intersects a water-filled passageway in carbonate rocks constitutes an artesian well. Depending on the existing head at the point, the water in the passageway can rise in the well to some level (a) above the ground surface, (b) between the ground surface and the water table, or (c) below the water table but above the passageway penetrated by the well. Hence, in areas where the piezometric surface is higher than the ground surface, wells (#1 and #2) intersecting these water-filled passages will be flowing artesian wells, and non-flowing for the opposite situation (#3 thru #6). Intermittently flowing artesian wells (#6) occur at sites where the piezometric surface and the ground surface intersect, inasmuch as both the water table and the piezometric levels rise or fall in response to conditions of precipitation.

2) For the water-table wells (#8, #9, #10) the depth to the water table is primarily a function of local topography, but the seasonal variation in water level depends upon position within the drainage basin (fig. 4). Greatest variation will take place at divides, least in the lowermost reaches of the drainage basin.

3) A flowing artesian well functions as an effective outlet and results in a loss of head, greatest at the well but diminishing rapidly radially. This effect produces a cone of pressure relief in the piezometric surface. Other flowing wells situated within the influence of this cone are affected. The situation is analogous to a household faucet when another is opened elsewhere in the dwelling. Each flowing well develops its own cone of pressure relief which, if closely spaced, will combine to form a composite cone. With more and more new flowing wells, the combined discharge in time will exceed the natural recharge into the passageways of

the carbonate rocks. Hence, the piezometric surface declines to or below the ground surface with the consequent failure of flowing wells within the area. The cone of pressure relief must not be confused with the cone of depression that develops around a pumped water-table well (#10). The latter involves the actual dewatering of sediments below the level of saturation in the unconfined, or water-table, aquifer. The subterranean passageway, on the other hand, remains completely filled but the pressure of water contained within it has been reduced. A non-flowing artesian well requires a pump. When in operation, a cone of pressure relief also develops but, in this case, lies beneath the ground surface. When pumping is discontinued, the cone recovers. The effect of this recovery on nearby wells is analogous to the recovery of water pressure and discharge from a household faucet when others in the dwelling are turned off.

4) Exchanges of water between bedrock and the unconfined and confined aquifers in the glacial overburden is a common occurrence. A high capacity water-table well (#10) can produce a large and deep cone of depression which creates, at that point, a water pressure differential. This induces movement of water from the secondary openings and pores in the bedrock into the overlying materials, especially into the more permeable sands and gravels. Such transfer is again termed crossbed leakage. Conversely, the heavy withdrawal from an artesian aquifer (well #5) produces a water pressure differential in an opposite direction leading to crossbed leakage from the overburden materials into bedrock.

5) Though ground water is frequently described as being under both confined (artesian) and unconfined (water-table) conditions, both should be considered parts of a single hydrologic system. They are not completely separate and independent entities.

Wells in bedrock aquifers are usually completed by setting a steel casing through the drift and into rock a few feet; the remainder of the hole is left uncased. Zones of primary porosity in carbonate rocks are usually inconsistent; permeabilities seldom permit yields in excess of a few gallons per minute. Thus, adequate yields form carbonate rocks depend largely on the number and size of the secondary openings intersected by the well. Primary porosity is important because it provides storage water eventually released to subterranean passageways. Though this transfer may seem insignificant per square foot of interface between the porous rock and the secondary opening, the volume transferred per square mile is indeed great. As operating wells reduce the head in the passageways, some induced drainage of pore water takes place.

Recharge by precipitation keeps the ground-water system dynamic. How well it functions as a dependable source of water supply between periods of precipitation, or during prolonged droughts, is partly related to storage. The porosity of the drift constitutes a potential for storage which, if saturated, could contribute to the recharge of the underlying carbonate aquifers (fig. 14). Storage becomes even greater if the rocks also possess some primary porosity. Where lacking, or ineffective, as in highly crystalline varieties of limestone and dolomites, storage is restricted to the secondary openings. Recharge of these openings depends upon the release of water from the overlying drift. Where this cover is thin and clay-rich, then recharge to the subterranean passages could be inadequate as ground-water withdrawals from wells increases.

A regional lowering of the water-table surface below the carbonate rock-drift boundary should suggest why the usual concept of the water table is abandoned. Without an effective primary porosity, a mass of rock bounded by bedding planes, joints, and fractures cannot become saturated even when these secondary openings are completely filled with water. Where the water-table surface drops below the bedrock-soil boundary, perched ground-water conditions are expected in unconfined aquifers in the drift.

Piezometric Map

The piezometric water-level map (Plate 6) is based on water levels reported on well logs for Monroe County during 1961-67. This time period represented corresponds to the "drought" in southern Michigan from December 1960 through December 1966. Since then, monthly precipitation has been normal, or above normal, a condition more favorable for ground-water recharge.

The contour lines on the map portray a piezometric (water pressure) surface for a complex system of joints, fractures and bedding planes -- not the water table. Well logs do not show the depth at which materials, regardless of induration or lithology, first become saturated with water--data needed for delineating the water table. Instead, each log indicates the level to which water rose in the well for the number of secondary openings penetrated in the carbonate rocks. In most instances, this level stood at some point above the bedrock-drift boundary and, in some cases, rose above the ground surface resulting in flowing artesian wells. In drift materials, artesian aquifers are found only in sand and gravel horizons partly, or wholly, enclosed by clay-rich materials. All Paleozoic bedrock strata constitute artesian aquifers inasmuch as they are more or less confined by overlying less permeable clay-till. Wells completed in confined sands and gravels are cased down to the waterbearing horizon and a well screen placed within the aquifer. Approximately 1450 water levels reported on logs of bedrock wells were used in compiling the piezometric water-level map.

Because the water-level data for this map spans a six-year period, the water-pressure surface portrayed by the piezometric contours is generalized, and therefore not representative of a given month or year. Like the water table, this pressure surface is also dynamic and responsive to changing conditions of precipitation and ground-water withdrawal by wells. Despite this limitation, the piezometric surface contour map, like a water-table map, still reflects the gross surface hydrologic and topographic features. Note that the piezometric surface declines southeast from an elevation of 680 feet, in the northwest corner, to 572 at Lake Erie -- a decline of 108 feet in 25 miles, or approximately 5 feet per mile. The conspicuous piezometric "high" in the southern part of Whiteford Township reflects the generally higher topography of the bedrock surface in that area. The steepest piezometric gradient is in Milan Township, a decline of 40 to 50 feet in a distance of one mile. The piezometric contours are influenced by major surface water features, particularly the Raisin River. The contours tend to bend upstream before crossing the stream; the 630-foot contour on both sides of the Raisin River trails off the map, doubtless converging somewhere in Lenawee County.

The broad depressions in the piezometric surface delineated by the hachured 570-foot contour line may be attributed to the effects of urbanization along the eastern margin of the county. Barbs of the contour lines point in the direction of lower values. Thus, bedrock wells within these enclosed depressions have piezometric levels usually below the level of Lake Erie (572 ft.). A large depression occurs in Berlin and Frenchtown townships in northeastern Monroe County; another in the southeastern area in Erie Township. The piezometric surface is not depressed in the City of Monroe and environs because the water supply is obtained from Lake Erie. The depressions reflect the domestic wells serving the many dwellings within the cities, villages, and resort areas situated along Lake Erie. To an extent, the northern piezometric depression is also influenced by nearby community and municipal well systems in both Monroe and Wayne counties and, perhaps, by quarry operations near Rockwood, Michigan.

The piezometric depression in Erie Township is the deeper of the two, as the 550-foot hachured contour encloses an area of considerable size and extends southward into Ohio where a number of high-yield wells are reported in the Toledo district. The small depressions within the large ones may neither be significant or permanent. Possibly they represent areas of higher, but localized, ground-water withdrawal, or, perhaps a lower water level was recorded on logs of new wells completed while nearby wells were being operated. Other large depressions located in Whiteford and Milan-London townships reflect numerous subdivision developments. The small depressions scattered elsewhere in the county also indicate small isolated subdivisions and, to some extent, the influence of high-capacity irrigation wells. A geologic structure, on the other hand is the reason for the several small depressions forming an arcuate pattern in Whiteford Township. This pattern coincides with the local flexure, or perhaps, a fault, shown on the county geologic map (Plate 1).

The stippled areas on the piezometric water-level map are principal flowing well districts delineated by W. H. Sherzer (1900). In 1961-1967 only eleven wells were reported as flowing. Nine of them are situated in the easternmost part of LaSalle and Monroetown townships between the two major piezometric depressions bordering Lake Erie. The other two are situated within the flowing well districts in Milan and Bedford townships.

Potential Sources of Contamination

The potential for ground-water pollution of bedrock aquifers in Monroe County is increased by the thin drift cover. Pollutants entering the subterranean channelways in the carbonate sequence are rapidly distributed over a wide area. A number of sand formations extend to the bedrock surface, literally functioning as conduits. Furthermore, the landscape has little relief resulting in a poor surface drainage and streams of low gradient. In places, the stream channels are at, or near, the bedrock surface. The coliform counts recorded in Table 1 evidence stream pollution; also, the analyses summarized in Table 2 suggest that pollution of ground water in bedrock aquifers is already occurring.

Year	River Raisin			Huron River		
	Min.	Max.	Median	Min.	Max.	Media
1963	360	1,400,000	140,000	91	23,000	4,300
1964	460	1,400,000	23,000	460	43,000	4,300
1965	3,600	460,000	93,000	300	240,000	4,300
1966	300	200,000	9,300	200	43,000	7,500

Table 1. Coliform counts in streams (Mpn/100 ml)

Source: Water quality records, Michigan Water Resources Commission

Direction of ground-water movement becomes important in any evaluation of subsurface water pollution. Determination of movement is seldom simple because the underlying materials are rarely isotropic. Even with the benefit of water-table and piezometric surface maps, it would be naive to conclude that water molecules necessarily follow a path perpendicular to the contour lines, that is, the direction of steepest hydraulic gradient. Furthermore, data for preparing such maps are not generally available in the desired number or distribution. Water level and pressure surface maps are generalized pictures, subject to a continually changing water cycle. Arnow's (1963) use of organic tracers in studying ground water in carbonate rock terrane revealed movement that closely paralleled the water level contours which, in the region, also paralleled the bedding, or strike, of the formations. The fact that movement was not perpendicular to the contours, as drawn on the map, suggests that, in layered rocks, horizontal and vertical permeability differences do exist.

Factor	No. determinations	No. samples in which R factor tested was present	Range ppm
pH	8	8	6.9 - 8.5
NO_3	107	48	0.1 - 20.2
NO_2	89	26	0.1 - 0.65
NH_3	2	2	5.0 - 112.0
ABS	114	19	0.1 - 5.0
H_2S	105	44	tr - 140.0
Phenols	6	4	tr - 0.01
Tannins	1	1	Indicated but not given
COD	2	2	192.0 - 3000.0
Fe	178	148	0.1 - 20.0
Cl	154	137	1.0 - 1650.0
F	103	97	0.1 - 2.0
Mg	4	4	48.0 - 187.0
Na	3	3	14.0 - 1200.0
SO_4	17	17	5.0 - 1620.0
$CaCO_3$	171	171	10.0 - 2030.0

Table 2. Results of 240 partial ground-water analyses in Monroe Co.

Source: Monroe County Health Dept.

Septic Tanks

Water is the principal agent in transferring contaminants downward to the water table. Of the several common sources of pollution septic tanks rank as one of the foremost problems. In a sense, they "rain" everyday as long as the dwellings they serve are occupied. A house with three occupants, each using only 100 gallons of water daily, would discharge nearly 2100 gallons of water weekly, 9000 gallons monthly, and 109,500 gallons annually. In sparsely populated agricultural areas, domestic wells and septic tanks are a practical solution to the basic needs of water supply and sewage disposal. However, agricultural lands in metropolitan areas are yielding rapidly to subdivision developments. With more and more septic tanks being crowded into limited parcels of land, a point is reached where ground-water resources are endangered and, in the interest of public health, their use should be curtailed as soon as practicable.

According to the metropolitan environmental study of sewerage and drainage facilities for the six-county area of southeastern Michigan (National Sanitation Foundation, 1964), the number of private septic tanks in Monroe County was estimated at 18,000 units. Since that study the number has increased significantly. If these units serve a population of 54,000 people this represents a total discharge into the soil of nearly 5.4 million gallons daily, 162 million gallons monthly, and 1.9 billion gallons annually. What happens to this polluted water after it is discharged into the soil?

Permits for septic tank installations are normally issued by the County Health Department, the policy for which is stated as follows (National Sanitation Foundation 1964, p. 52):

> "First of all, septic tank systems should be constructed only on a farm or exceptionally large lots having suitable soil conditions and, most importantly, public sewerage facilities are necessary for safeguarding public health in urban situation. Secondly, a septic tank system should not be constructed on any parcel of land, regardless of size, having unsuitable soil conditions (clay) because the system will certainly fail and create a dangerous health problem to the family and neighborhood."

Suitable soil conditions can be defined largely in terms of permeability which, in the field, is determined by percolation tests. Where surface materials show favorable percolation rates -- essentially sands and gravels -- these same materials, if saturated in their lower portions, often function as water-table aquifers (fig. 11). Pollution of water-table aquifers of glacial origin by septic tanks has been documented in Long Island (Perlmutter et al, 1964). It has also been demonstrated by the writer (litigation in Macomb County). In Monroe County the pollution of water-table aquifers would be limited to the surface sands thick enough to be saturated in their lowermost portions either by a true water table or a perched water table (fig. 8). However, subdivision developments comprised of dwellings served by individual water-table wells and septic tanks (fig, 15), are not known to this writer. Undoubtedly, scattered dwellings under such geologic conditions must exist in the sparsely populated areas of the county. Septic tank failures can occur even in "suitable" soil conditions, indicating factors other than percolation must be taken into consideration. Under water-table conditions (fig. 4), the depth to the water table is largely the function of local topography. Also the amount of seasonal variation of the water table depends upon geographic position within the drainage basin. Field percolation tests indicating favorable results during late summer or fall do not necessarily prove septic tanks will function properly the following spring, particularly when local topography and position within the drainage basin are not considered. Nor is a deeper water table any assurance that contamination will not occur-- only a longer period is required for contaminants to reach the water table.

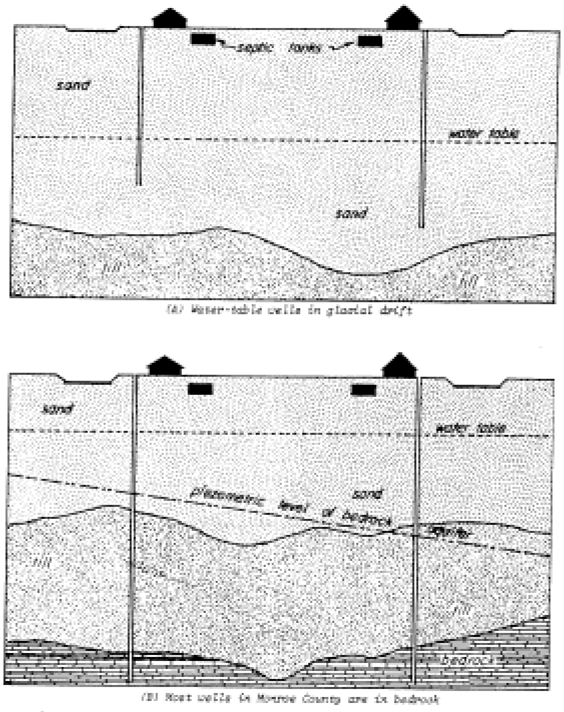

Figure 15. Despite the overlying till, wells in bedrock are not necessarily secure from contamination by septic tanks.

The number of water-table wells in the county is small. The more prevailing situation is illustrated in fig. 15. The presence of a clay-till does not necessarily secure the bedrock aquifer against pollution by the downward movement of septic tank discharge. Subsurface conditions at the particular subdivision site must be related to the surrounding region. Figure 16 (constructed from well logs) shows how a surface sand deposit can serve as a conduit to bedrock. Inasmuch as a township may contain many subdivisions with 100 or more dwellings, the gross daily volume of septic tank discharge into the surface sand is appreciable. Furthermore, ground-water withdrawal by hundreds of domestic wells, along with high capacity community or irrigation wells, reduces water pressure in the rock aquifer, and produces a differential causing polluted water to move from the unconfined surface sand into the rock aquifer. Sand-bedrock interfaces vary greatly in size and frequency of occurrence. When well records are abundant, these sand bodies can be plotted with sufficient accuracy to show lithologic changes with depth (fig. 17). Because much of Monroe County is underlain by carbonate rocks, with enlarged secondary openings beneath a thin overburden, surface water can move into and be dispersed rather easily. Infectious diseases can be spread rapidly under these geologic conditions. The hepatitis outbreak in Posen, Michigan, represents a documented case (Vogt, 1961).

Disposal of liquid wastes in sewage lagoons instead of individual septic tanks should not be undertaken unless the subsurface geology is known in detail (Bogan 1961). Discharge of many individual septic tanks is diffused over a larger area, whereas the sewage lagoon concentrates waste in a small area, and may not be practicable in urbanizing areas. Though providing a safeguard against ground-water pollution of a particular subdivision, other developments down-gradient may be exposed to a potential health hazard.

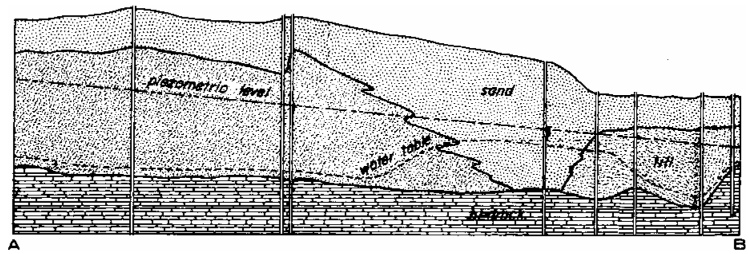

Figure 16. Sand bodies often serve as conduits for transmitting both potable and contaminated water to bedrock aquifers.

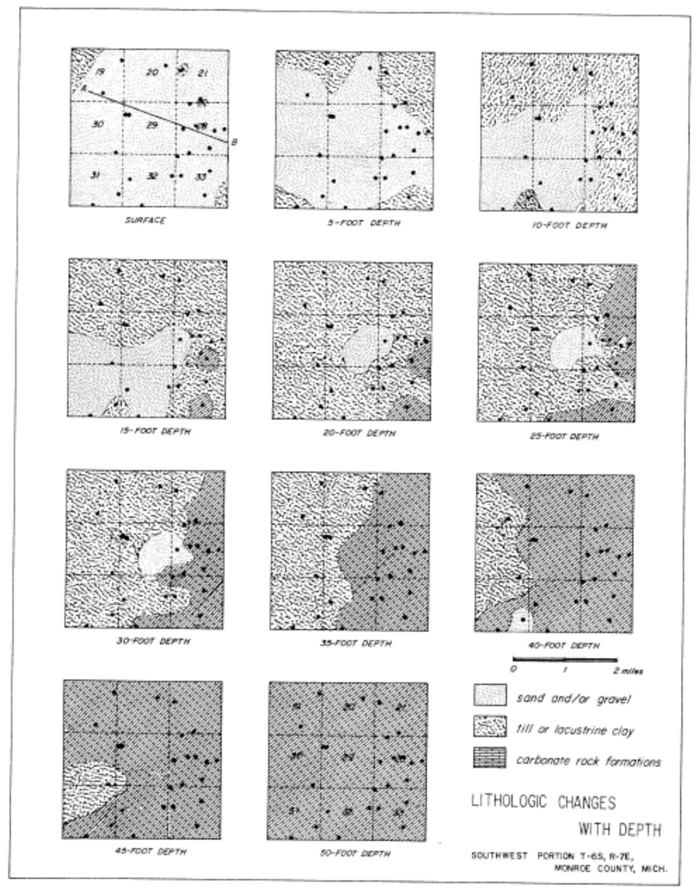

Figure 17. The lithology of glacial drift may change with depth.

Infiltration From Surface

Closely spaced domestic wells and high-capacity community or irrigation wells produce either cones of depression or pressure relief, depending on the occurrence of ground water. In either case, with continuing and increasing rates of pumpage, these cones eventually coalesce and grow in size until they intercept surface water bodies. The resulting reversal of the water table or piezometric gradient encourages infiltration of surface waters into underlying aquifers. Depending on the thickness and type of overburden through which polluted water must pass before reaching an aquifer, the contaminants will consist largely of soluble compounds. Where carbonate rocks are near the surface along stream courses, the prospect of bacteriological contamination becomes imminent (table 1).

Fertilizers and Pesticides

In a carbonate rock-glacial drift terrane in Missouri, Smith (1964) discovered the infiltration of animal and human wastes to be the main source of nitrates in water supplies. Given certain geologic conditions, the indiscriminant application of pesticides, herbicides, and chemical and organic fertilizers can contaminate the ground-water resources. Because surface water and ground water are parts of the same system, the presence of these compounds in the subsurface water environment, even though in small amounts at present, must be heeded.

Quarries and Sinkholes

Quarries and sinkholes have been used for the disposal of man's wastes. These man-made and natural features, however, provide a rapid means for surface contaminants reaching carbonate aquifers and moving along subterranean passageways. Quarries and sinks appearing on Plate 1 were plotted from Sherzer (1900), from field visits, and other sources. Investigating subsurface geologic conditions is undeniably important in minimizing ground-water pollution from sanitary landfill operations.

Mineral and Disposal Wells

The hazards of contaminating bedrock aquifers and mineral reservoirs as a result of drilling wells and bores have long been recognized. Control of the drilling, operating, and abandoning of mineral, brine, test, waste disposal, or storage wells is now prescribed by Act 315 of the Public Acts of 1969 (Michigan). Information on regulations pertaining to this activity should be directed to The Supervisor of Mineral Wells, Geological Survey Division, Michigan Department of Natural Resources.

Drainage Wells

This practice was commonplace years ago in the agricultural areas, as noted by the expression "farm drainage well" on old records. It is now prohibited by the County Health Department and the State of Michigan. However, occasional violations have been known to occur. Sherzer (1900) cites one instance where a dry exploratory oil well was used for draining surface waters in a quarry.

Artesian Spring Failures

Since 1900 there has been a decline of the piezometric level in Monroe County (Plate 6). Hence, any artesian spring whose flow has ceased implies that its opening can now receive surface waters in much the same manner as a drainage well.

SUMMARY

Monroe County is extensively underlain by limestones and dolomites with some shale and sandstone present in the stratigraphic sequence. The bedrock surface, dissected by numerous shallow and deep valleys, exhibits a maximum relief of nearly 220 feet. The bedrock is covered with drift ranging from a few inches to a maximum of 160 feet. Over more than two-thirds of the county, however, the drift does not exceed 50 feet in thickness. Drift in excess of 50 feet is associated with buried rock valleys and not with topographic highs inasmuch as the present ground surface is nearly flat lacustrine plain.

The shallow depth to bedrock is a factor favorable for the development of rock resources and in the selection of sites for heavy industries where foundation costs are an important concern. A shallow rock depth is not favorable with respect to water and sewer projects, or other underground public utilities, because of the higher costs associated with rock excavation.

Except for the cities of Monroe and Dundee, the county depends largely upon the ground-water resource for its water supply, and will continue to do so for some decades ahead. About 90 percent of the wells are completed in bedrock. Wells completed in artesian aquifers in glacial drift are located mainly along buried bedrock valleys. Despite the extensive occurrence of lacustrine, beach, and dune sands, shallow wells in these deposits are not numerous because they are relatively thin and underlain by a blue-gray till. The shallow domestic wells, whether drilled, dug, or driven, are usually found where the surface sands are thickest and underlain by till, or, where they extend to the rock surface. The former situation implies limited water storage and, perhaps, perched water-table conditions. The latter is a more favorable situation because water withdrawn from the sand aquifer is generally replaced by the upward movement of artesian water from the underlying bedrock.

Pollution of the ground-water resource is a distinct hazard. In fact, ground-water analyses already indicate pollution. The principal source for ground-water pollution appears to be from septic tank concentrations as found in subdivisions. The potential sources and areas of ground-water pollution need to be identified and quantified.

Geologic maps depicting subsurface conditions are useful to construction projects in that unexpected problems resulting in loss of time might be anticipated in advance. They are helpful in evaluating the county's rock and minerals resources and, above all, are essential to multiple and sequential land-use planning. The several maps included with this report should not be considered as final but simply as interim "base" maps upon which new data can be plotted as acquired.

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APPENDIX

DESCRIPTION OF ROCK UNITS BENEATH DRIFT IN MONROE COUNTY

Note: Only rock units immediately beneath the glacial drift in Monroe County are described in this report. The following descriptions are based essentially on oil and gas logs supplemented by published geologic literature and field observations. Thickness values apply to Monroe County only.

Antrim Shale (Late Devonian)

Lithology: Dark brown to blacks crisp, fissile, finely-laminated, bituminous shale frequently termed "black slate" by well drillers and occasionally mistaken for coal. When fragments are burned, or heated, an odor of burning coal is strongly noticeable. Some thin gray shale members usually present near base. Pyrite and/or marcasite (iron sulfide compounds) usually present, either dessimated, or as spherical or irregular nodules. Weathers gray or rust-brown, the latter, usually caused by the oxidation and hydration of iron compounds. Two characteristics are useful in identifying the unit in the subsurface. First is the presence of hard, dark-brown to black, crystalline and nearly spherical concretions often present in the lower part. These concretions are composed of "anthraconite", a petroliferous variety of calcium carbonate. When large, exceeding 2 to 3 feet in diameter, the drill cuttings may mistakenly be logged as limestone beds. An excellent exposure of the Antrim Shale occurs at Kettle Point, Ontario, which took its name after the large spherical concretions resembling kettles awash in the surf. The other characteristic is the abundant presence within the formation of minute, but visible, disc-like structures having thick walls and a pitted, reddish-brown, resinous appearance. These have been identified as fossil spore cases of floating plants *Sporangites huronensis*. The origin of these structures, called Tasmanites, is uncertain.

The Antrim contains "shale gas" but the formation has not been developed as an important producer anywhere in Michigan. Where the formation is directly overlain by glacial drift, the shale gas may seep into the overlying permeable sediments. Drillers, particularly in Wayne, southeast Oakland, and in southern Macomb and St. Clair counties, frequently record the presence of this gas while drilling in glacial drift deposits. The gas may occur in pockets with pressures up to 35 Ibs. per square inch; or it may occur with ground water. Old geologic reports for areas in southeastern Michigan (Sherzer 1916, also others) contain frequent references to the presence of this gas both in the Antrim Shale and in the overlying drift. This gas constitutes a hazard in excavating and in ground-water development projects. Even in recent years explosions causing damage to equipment and structures, injury, and death have been reported. A few years ago, two workers were asphyxiated in a sewer construction project. In October 1968, a test hole for a foundation design in northeastern Wayne County was observed to be filled with water that was actively bubbling. Gas present in the water was sampled and identified as "methane". Predicting where, when, at what depth, or pressure this gas may be encountered, either in the Antrim or the overlying drift, is difficult. Therefore, it is wise to assume the presence of this gas, and to exercise safety precautions while drilling or excavating. Water well records collected for Monroe County within recent years show only one specific reference to gas in the Antrim Shale in an area just west of the Village of Ottawa Lake. Other references are mentioned in Sherzer's (1900) geological report for Monroe County.

The lower contact of the Antrim rests conformably on the Traverse Group. The basal gray-colored beds are not easily differentiated from the underlying blue-gray shales next to be described. *Thickness:* 0 to 150 feet; 150 to 175 feet in Ann Arbor (Ehlers et al, 1951). *Outcrop Area:* Small scattered areas beneath the glacial drift; most likely along the western boundary of Whiteford Twp. *Exposures:* None.

Traverse Group (Middle Devonian)

Lithology: Consists of shales and limestones and dolomites, with their shaly counterparts. Not subdivided into distinct and separate formations in the subsurface of southeastern Michigan. Pyrite is relatively common throughout the section. The shale horizons are blue-gray, occasionally brownish, and may contain some thin calcareous or dolomitic beds or lenses. The carbonate rocks, limestone and dolomite, can be thinly or massively bedded and occasionally very cherty. Limestone beds are light-gray, gray, bluish-gray, and at times brown with textures ranging from finely to coarsely crystalline. At times, the beds may be richly fossiliferous. Individual corals, coral reef structures, and bioherms are not uncommon. The dolomites, and their shaly counterparts, are normally gray or buff, thinly to massively bedded, and somewhat more coarsely crystalline in texture. The ratio of carbonate rocks to shale within the total section of the Traverse Group can vary considerably from one area to another in the southeastern Michigan region. Changes in ratio from place to place are gradual.

The lower half of the Traverse is exposed in quarries near the Village of Silica, just south of Sylvania, Ohio. This portion of the section has been subdivided into the Silica Formation and the overlying Ten Mile Creek Formation. The Silica Formation, 55 feet thick, consists of a "blue" limestone at its base, succeeded by shales with occasional limestone beds and, finally capped by massive limestone. The overlying Ten Mile Creek Formation, of which only 38 feet remain exposed beneath the glacial drift deposits, consist predominantly of dolomites with occasional shaly dolomites and dolomitic limestones. The beds are bluish-gray, light gray, brownish-gray to drab. Textures are fine grained to crystalline with coarser textures more common near the base. These two units show a northward continuation and thickening into southeastern Michigan. Also, some of the limestones grade into shales (Ehlers et al, 1951).

The contact of the Traverse Group with the underlying Dundee Limestone is difficult to define where the contact is comprised of limestones in both units. This appears to be the case at Silica, Ohio, in Milan Twp., Monroe County, and adjacent Macon Twp. in Lenawee County. Around the Northville area in Wayne County, the contact is reasonably sharp inasmuch as shales prevail near the base of the Traverse. *Thickness:* 0-175 feet in Macon and Clinton twps., Lenawee County. *Outcrop Area:* Only lower portion of the Traverse outcrops beneath the drift, principally in the northwestern one-third of Milan Twp., and along the western county line southward into Ohio. Some outliers are present in Milan Twp. associated with bedrock knobs or upland tracts between well defined bedrock valleys. This relationship becomes more evident if the bedrock topography map is used in conjunction with the geologic map. *Exposures:* None. Lower portion exposed in quarries near Silica (Lucas County) Ohio, and formerly in quarry, now water-filled, east of Milan in Washtenaw Twp., Michigan.

Dundee Formation (Middle Devonian)

Lithology: Gray, bluish-gray, buff-light brown limestones, dolomitic limestones, and dolomites. Thin to massively bedded with finely to coarsely crystalline textures, and containing cherty and/or siliceous horizons. Shale beds occasionally appear in the sequence. The type locality is at Dundee, Michigan, where its exposure in the old Christiancy Quarry situated in the flood plain of Macon Creek, revealed beds of high-calcium limestone suitable for cement and lime. Although the Dundee is normally a limestone, it may also be a dolomitized limestone. At the quarry in Trenton, Michigan, about 70 feet of the Dundee are exposed consisting of bluish, thinly to massively bedded limestones containing cherty and siliceous horizons, some highly fossiliferous zones, and secondary calcite. Carbonaceous partings between limestone beds, and cavities containing hydrocarbons are common. Grains of frosted quartz sand are abundant in the basal beds. The Dundee exposed near Silica, Ohio, consists of high-calcium limestone beds nearly 62 feet thick. When limestone prevails as the dominant lithology analyses frequently exceed 98.5 percent calcium carbonate. In the subsurface, a limestone lithology prevails in the Milan area; dolomites generally succeeded by limestones in London Twp., Monroe County, and in Macon and Clinton twps. of Lenawee County a mixed dolomite-limestone lithology. The lower contact of the Dundee may be difficult to place in the subsurface inasmuch as the underlying Detroit River Group also consists of formations containing limestone and dolomite sequences. *Thickness:* 0-117 feet, up to 150 feet in Macon Twp. in Lenawee County. *Outcrop Area:* As a broad band trending northeast-southwest through London, Milan, and Dundee twps., thence turning sharply to the south and narrowing in width along the west margin of the county into Ohio. Some outliers of the Dundee occupy the higher bedrock knobs in London and Dundee twps. *Exposures:* Active quarry of Dundee Cement Company two miles north of Dundee, Michigan; quarries at Silica, Ohio, and Trenton, Michigan. Former quarries and/or natural exposures of the Dundee are indicated on the geologic map.

Detroit River Group (Middle Devonian)

Where exposed in several quarries around Silica, Ohio, this group has been subdivided, in descending order, into the Anderdon (24 ft. thick), Lucas (84 ft.), Amherstburg (19 ft.) and Sylvania (50 ft.) formations. With the exception of the Sylvania, characterized by a quartz-sand lithology, the units have a carbonate lithology difficult to differentiate in the subsurface. For this reason the Detroit River Group appears on the geologic map of Monroe County as two separate rock units, one a non-clastic, the other a clastic. The upper unit includes the three carbonate formations. The Sylvania Sandstone is the other, but older, unit at the base.

Lithology of Detroit River Dolomite: Dominantly dolomites, some limestones, occasionally cherty and/or argillaceous. Gray, buff, light-brown, or white with textures ranging from finely crystalline to granular. The Anderdon Formation, uppermost in the section, is a high-calcium limestone that cannot be readily differentiated in the subsurface from the overlying Dundee Limestone. Dolomite beds can be expected within the Anderdon. The remainder of this rock unit (Lucas and Amherstburg formations) are nominally dolomites of varying thickness. Irregular cavities are common, frequently lined with calcite crystals usually in a form known as "dog-tooth spar" and measuring up to 3-4 inches in length. At the quarry near Maybee, occasional masses and crystals of native sulfur have been found. Anhydrite occurs in the section, particularly in the Lucas Formation, in lenses or thin beds of limited extent. The amount of frosted quartz sand grains, similar in appearance to those of the Sylvania Sandstone, increase in the basal beds. The lower contact of the Detroit River Dolomite usually occurs at the first persistent occurrence of sandstone, or dolomitic sandstone, of the underlying Sylvania Sandstone. _Thickness:_ 0-197 feet. _Outcrop Area:_ As broad band trending northeast-southwest across northern third of county, and thence, abruptly narrowing in the western part of the county and turning south into Ohio. Where the overlying Dundee has been incised by deep bedrock valleys, the Detroit River Dolomite can appear in outcrop along the floor of the valley as "windows", as in a valley 3 miles northwest of Petersburg and again at Azalia. An outlier of this unit is present at Carleton in Ash Twp. _Exposures:_ In quarry of Michigan Stone Company about 1 mile west of Scofield in Exeter Twp.; County Road Commission quarry, Sec. 13, Raisinville Twp.

Lithology of Sylvania Sandstone: White to light gray, fine to medium high-purity quartz sandstone. The individual grains are frosted and subangular to rounded, poorly cemented and extremely friable upon exposure to weathering. When crushed, washed, and screened, resembles granular sugar; terms such as "sugar-sand" and "silica sand" are common notations on driller's records. Best exposure of the Sylvania is found in a quarry operated by the Ottawa Sand Company, previously known as the Michigan Silica Company, about one mile southeast of Rockwood in Wayne County. About 33 feet of the sandstone can be seen in the quarry walls. Where exposed to weathering for some time, a dull gray appearance predominates, in contrast to a nearly pure white color on freshly quarried faces. Fresh cuts clearly reveal a widely-spaced joint pattern, some irregular fractures and bedding. Seams of carbonaceous (?) material apparent on fresh cuts occur at varying intervals. Cavities (geodes) are lined with calcite and celestite as crystals. On rare occasions native sulfur may be found in the geodes. Below the quarry floor, in the walls of the primary crusher pit, is still another 57 to 62 feet of the Sylvania Sandstone including 15 feet of sandy dolomite which is light to dark gray with some zones of chert nodules and dolomite pebbles. The Sylvania may grade upward into the dolomite beds of the Amherstburg Formation, the boundary both being very difficult to recognize in the subsurface as well as in outcrop. Hence, the difficulty in accurately determining the thicknesses of the formations comprising the Detroit River Group. The Sylvania rests nearly everywhere on the Bois Blanc Formation except for a small area in southern Michigan and northern Ohio. In Monroe County, the basal beds rest unconformably on the Bois Blanc Formation and the Bass Islands Group. In Ohio, pebbles derived from the Raisin River Dolomite (of Bass Islands Group) have been identified in basal Sylvania. _Thickness:_ 0-288 feet. Where overlain by younger beds, the Sylvania Sandstone thickens to the north and west. In the southwestern corner area of the county and at Silica, Ohio, the Sylvania Sandstone is approximately 50 feet; greatest thickness reported is in the northern part of London Twp. _Outcrop Area:_ Initially as a wide but rapidly narrowing band trending diagonally across the middle of the county, thence turning sharply to the south in Summerfield Twp. towards Ohio. Some windows and outliers are also present. _Exposures:_ Formerly exposed at Toll Pits in Sections 2 and 3, Raisinville Twp.; in trench of Cummins Quarry in Sec. 11, Whiteford Twp., and along floor of quarry at Lulu, Sec. 16, Ida Twp. Best exposed today at an active quarry near Rockwood, Michigan in Wayne County.

Bois Blanc Formation (Middle Devonian)

Not shown as a rock unit on the county geologic map because of difficulty in recognizing its boundaries and correlating between areas due to scarcity of records. Both the upper and lower contacts of the Bois Blanc are marked by erosional unconformities and, therefore, the thickness can vary greatly from place to place. Though reported as eroded in southern Michigan and northern Ohio in pre-Sylvania time, its removal was not necessarily complete everywhere in the region. Remnants of the Bois Blanc Formation within its projected outcrop area beneath the drift remain a possibility and, if recognized, may occur on the bedrock surface knobs. More records are needed before the outcrop area or its erosional remnants can be delineated in detail.

Lithology: In both subsurface and outcrop the formation is largely cherty and fossiliferous carbonate rock, usually light colored. Dolomite prevails although in some areas limestone may dominate. Chert appears to be more abundant in the lower portion. Only one oil and gas log reports Bois Blanc immediately beneath the drift. The majority of the records indicate the presence of Bois Blanc in areas where it is succeeded by geologically younger strata. The Bois Blanc appears to have a lithology dominated by dolomites, light gray to gray-brown, tan to light brown, or medium brown, and with fine- to medium-grained textures. Chert is abundant throughout the section and, perhaps, represents a useful criterion for the recognition of the Bois Blanc. Some horizons are exceedingly chert-rich, up to 20 percent reported, which may imply weathering, especially if the chert itself shows signs of chemical decomposition and staining by iron oxides. The chert is highly variable; it can be hard, smooth, occasionally vitreous, and often characterized by conchoidal fractures. It may be white, light to dark gray, brownish-gray, or bluish-gray. Siliceous zones or cherty streaks within dolomite and limestone beds are also present. *Thickness:* Highly variable within short distances laterally. Varies from 0-125 feet. *Outcrop Area:* Not shown due to inadequate records. *Exposures:* None.

Bass Islands Group (Late Silurian)

Lithology: Includes the Raisin River and the underlying Put-in-Bay dolomites which are usually not separated in the subsurface. Within the county, the Bass Islands Group consists largely of light gray, tan, buff, brown, or dark brown and dense to finely crystalline dolomites and some shaly dolomites. In some areas the rock may be generally gray, tan, buff or brown, dense to finely crystalline limestone with vugs, tiny fractures, crevices, porous zones. Gypsum and anhydrite in thin beds, nodules, or stringers, as well as clear selenite, occur more commonly than in overlying rock units. *Thickness:* 0-302 feet. *Outcrop Area:* Broad, diagonal band in the southeast half of the county. *Exposures:* Active quarries in Whiteford and Monroetown twps.

Salina Group (Late Silurian)

Near the center of the Michigan basin the thickness of the Salina Group exceeds 4,500 feet with salt beds constituting nearly one-half the total section. Outside Monroe County, within the deeper parts of the Michigan basin, this group is subdivided in the subsurface into seven formations designated alphabetically as follows (in descending order): *G Unit* -- Green to red shales; 40-100 feet; *F Unit* -- Thick salt beds separated by anhydritic shale and/or shaly dolomite. Youngest salt-bearing member of the group. Dolomites are usually gray, buff, brown. Greatest thickness reported 1,230 feet; *E Unit* -- Gray or red shale with interbedded dolomites and shaly dolomites; 100 ± feet; *D Unit* -- Salt; 25-65 feet; parted by dolomite bed; *C Unit* -- Greenish-gray shales and shaly dolomites; 60-160 feet; *B Unit* -- Nearly pure salt with some dolomite as thin layers or stringers; 400 ± feet; *A Unit* -- Dolomite with two large salt horizons 870 feet thick; maximum thickness of unit 1100 feet.

The A and B units constitute primarily the carbonate-evaporite section of the Salina. The overlying C through G units primarily the clastic-evaporite section. Evaporites include salt, gypsum, and anhydrite beds. The Salina thins towards the rim of the basin as a result of leaching and/or non-deposition of the evaporite members. At some localities along the rim of the basin, the entire Salina section may be represented by less than 200 feet of sediments.

Lithology: The Salina Group consists largely of dolomites and shaly dolomites, with appreciable amounts of shale, dolomitic shale, and alternating shale-dolomite sequences particularly in the upper portion. The dolomites are usually gray, buff, light brown, or brown and dense to finely crystalline, but occasionally coarse. Anhydrite and gypsum are commonly associated with the dolomites but salt is rarely present. The dolomites are further characterized by stylolitic seams, black shale or carbonaceous partings, vugs, crevices, porous zones and, in some instances, cavernous in the upper part of the section. Hydrocarbons (often as black oil in pores), petroliferous odors, and shows of gas are not unusual. The shale beds are usually gray, but green, greenish-gray, minor amounts of red. The shale beds may contain some dolomitic beds or stringers, gypsum, and anhydrite oil and gas shows. The gypsum content is often sufficient to classify the rock as gypsiferous shale. Anhydrite occurs as distinct beds 5 to 15 feet with stringers, or inclusions, of shale or dolomitic shale. Within the total Salina section gypsum is usually massive, white, and in thin beds, stringers, and nodules. Selenite and satin spar, though very minor in amount, are frequently reported in the oil and gas logs. The most distinctive characteristic is the apparent absence of salt beds (only one instance of a 5-foot bed), in marked contrast to the considerable aggregate thickness of salt (730 feet) in Wayne County immediately north. The contact of the Salina with the underlying Niagara in Monroe County is not easily determined in the subsurface but probably occurs at the bottom of the lowest anhydrite bed. *Thickness:* 0-820 feet. *Outcrop Area:* Along southeastern-most portion of the county. *Exposures:* None.

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