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SINKHOLES AND SINKHOLE PROBABILITY

By

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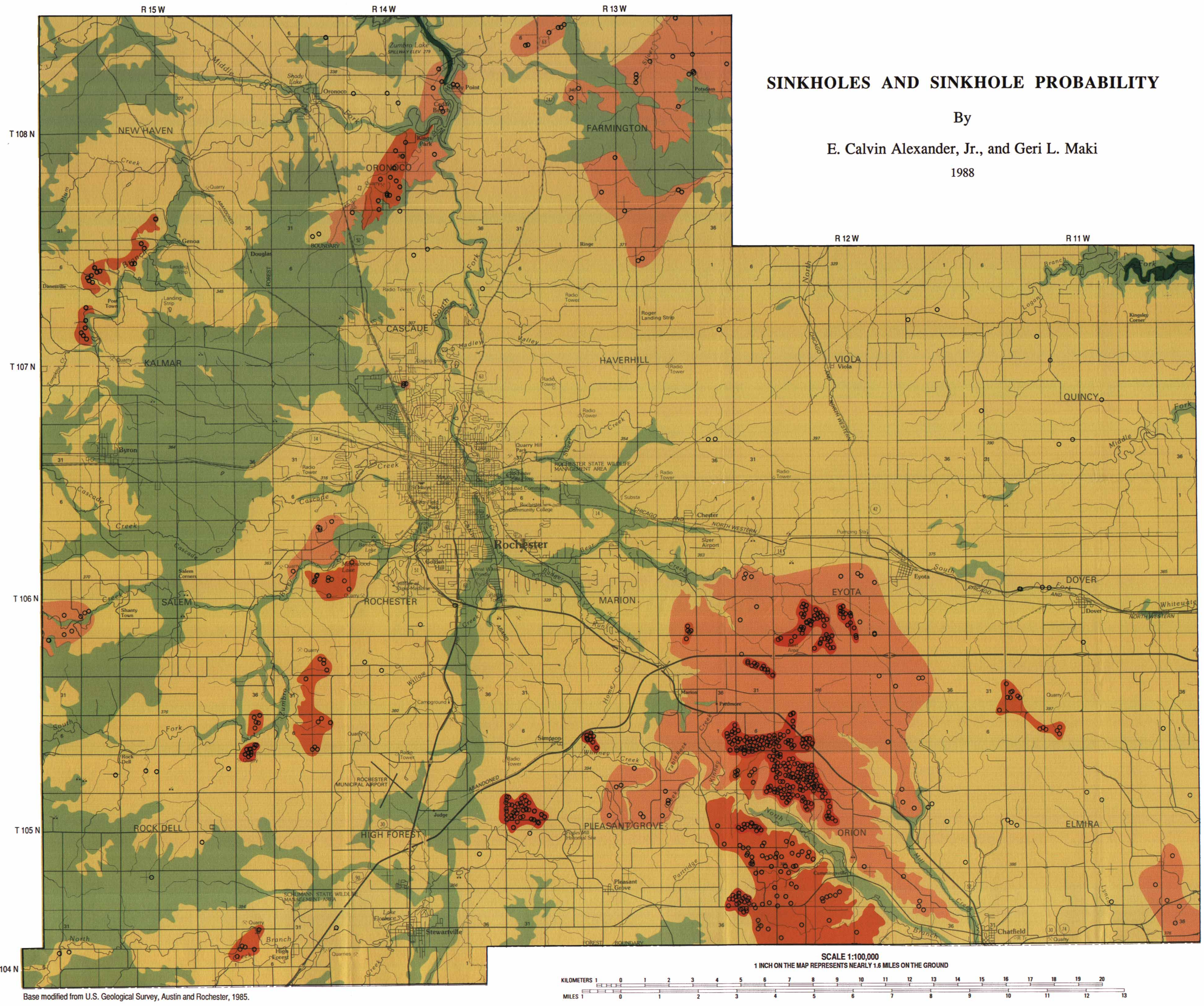

SCALE 1:100,000
1 INCH ON THE MAP REPRESENTS NEARLY 1.6 MILES ON THE GROUND

KILOMETERS 1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
MILES 1 0 1 2 3 4 5 6 7 8 9 10 11 12 13

Base modified from U.S. Geological Survey, Austin and Rochester, 1985.

EXPLANATION

Local residents provided most of the information on sinkhole histories and locations. Other sources of sinkhole locations include the Soil Conservation Service, air photos, and U.S. Geological Survey topographic maps. Although the entire county was systematically searched for sinkholes, coverage of the county was least complete in forested areas and where access to the land was unobtainable. The 865 sinkholes inventoried probably include about 75 to 80 percent of the sinkholes, both open and closed, in Olmsted County. Of the 865 sinkholes, 8 to 10 percent have been closed and are no longer visible on the land surface.

The construction of the sinkhole probability map was guided by a very similar effort in Winona County (Dalgleish and Alexander, 1984a, b). The relative likelihood for future sinkhole development was estimated primarily on the basis of the observed density of sinkholes. Surface collapse is most likely in areas where sinkholes are concentrated (Kemmerly, 1982). In places where fewer sinkholes occur, a chance still exists that new sinkholes will open in apparently random locations. The major secondary controls appear to be depth to bedrock (Plate 4) and bedrock geology (Plate 2). The division of the county into areas of varying sinkhole probability should be viewed as approximate, not as sharply defined boundaries.

NO SINKHOLE PROBABILITY

The only places in Olmsted County where sinkholes cannot form are one small area along the Whitewater River in the extreme northeastern corner of the county and another small area along the Zumbro River in the extreme northern part of the county. In these deep river valleys erosion has removed all of the carbonate bedrock. The rest of the county has some potential for sinkhole development.

LOW PROBABILITY

Areas underlain by carbonate bedrock, but in which essentially no sinkholes were observed, are shown on the map as having low probability for sinkhole development. In Olmsted County, very few sinkholes were observed where there is more than 50 feet of cover over bedrock. Most of the low probability areas are over buried bedrock valleys that contain more than 50 feet of till.

In Winona County (Dalgleish and Alexander, 1984a) sinkholes in the Oneota Dolomite were not observed on the steep slopes along deeply incised valleys, presumably because surface water tends to run off rather than to infiltrate into the bedrock. However, these steep slopes and bluffs do contain abundant evidence of past karst solution, such as caves and enlarged joints. If new sinkholes do form, they may not be noticed because of the rapid erosion of the downslope rim of the sinkhole and filling of the sinkhole with sediments. In Olmsted County, this environment is present in the extreme northern and northeastern areas.

LOW TO MODERATE PROBABILITY

Much of Olmsted County is underlain by carbonate rock covered with only a thin layer of surficial material, but contains only widely scattered individual sinkholes or isolated clusters of 2 or 3 sinkholes. The average sinkhole density is less than one sinkhole per square mile. The expected future sinkhole development is generally low in these areas, but is moderate where small sinkhole clusters have developed. The upper bedrock ranges from the Maquoketa Formation down through the Oneota Dolomite of the Prairie du Chien Group. Much of this region is drained primarily via infiltration into the ground water, and exhibits all of the ground-water contamination problems of the areas having high sinkhole densities. The near-surface carbonate aquifers are clearly karst aquifers, although not many sinkholes are evident on the surface. The presence or absence of sinkholes alone is not a sufficient predictor of susceptibility of the ground water to contamination (Plate 6).

MODERATE TO HIGH PROBABILITY

In parts of Olmsted County, sinkholes are a routine part of the landscape. They occur as diffuse clusters of three or more sinkholes, and the average sinkhole density is about 1 to 5 per square mile. These areas are scattered from the northern to southern parts of the county and from the west-central edge to the southeastern corner. These areas of moderate to high probability are underlain by any of the carbonate bedrock units. In these areas the sinkhole density becomes a significant engineering concern, especially for large facilities.

HIGH PROBABILITY

Where their density reaches 5 to 20 sinkholes per square mile, sinkholes are a common part of the landscape. New sinkholes periodically appear and many more are expected to form. Small areas where sinkholes are less common were included in this category because they do not differ in geology or topography from the rest of this map unit. Clusters of sinkholes may develop in response to local changes, such as fluctuation of the water table, construction of a building or water-retention facility, or hydraulic changes being created now by isolated sinkholes. Areas of high sinkhole probability occur over all of the carbonate bedrock units and are scattered from the northern to south-central parts of the county. Several, but not all, of them are on local highlands adjacent to river valleys. The steeper hydrologic gradients near the valleys may be contributing to the karst erosion which is producing these high densities of sinkholes.

KARST TOPOGRAPHY

In parts of south-central Olmsted County, roughly south of Eyota, Marion, and Simpson, the density of sinkholes ranges from 20 to several hundred per square mile. Sinkholes are the dominant landform. Essentially all of the precipitation that is not lost to evapotranspiration either infiltrates or runs into a sinkhole. New sinkholes often appear. Sinkholes are a major problem for agriculture and prevent the cultivation of a significant fraction of many fields. Sinkhole collapse is a major, ongoing concern for roads and any structures or facilities.

All of these areas are underlain by Galena Group rocks. The area in southern Olmsted County appears to be the most northern occurrence of the very high sinkhole densities that extend southeastward across Fillmore County into northeastern Iowa.

INTRODUCTION

In Olmsted County, mildly acid ground water is slowly dissolving the carbonate bedrock, producing distinctive ground-water conditions and landforms called karst. Karst aquifers are highly susceptible to ground-water contamination because solution-enlarged fractures and sinkholes form passageways that funnel water from the surface into the ground-water system, and interconnected cavities allow the water to disperse rapidly over considerable distances. At the surface, the collapse of unconsolidated rock material into sinkholes can cause structural damage to all types of facilities.

The effects of karst extend over a much greater area than that directly underlain by carbonate bedrock. Ground water flowing through the karst aquifer eventually moves into lower aquifers and discharges from springs near the bottom of valleys. The water flowing from springs commonly carries surface contaminants, and the water is generally high in calcium, magnesium, and bicarbonate ions dissolved from carbonate bedrock.

KARST PROCESSES

Dolomite, the most common carbonate rock in the county, is primarily composed of the mineral dolomite—$CaMg(CO_3)_2$—plus some limestone. Limestone is primarily composed of calcite—$CaCO_3$—plus some dolomite. These are not the only soluble rocks in which karst can develop, but they are the only soluble rocks in Olmsted County.

As surface water percolates through the soil, carbon dioxide from the air and from biological activity in the soil dissolves in the water. The water (H_2O) and carbon dioxide (CO_2) chemically form carbonic acid (H_2CO_3), a weak acid which reacts with calcite and dolomite, causing the rock to dissolve slowly. The process of dissolving the carbonate bedrock involves a series of chemical reactions, as explained by White (1988). The general equation for carbonate solution, a summary of several reactions, is as follows:

$$CaMg(CO_3)_2\ \text{(dolomite)} + 2H_2O + 2CO_2\ \text{(dissolved)} \rightleftharpoons Ca^{++} + Mg^{++} + 4HCO_3^-$$
$$CaCO_3\ \text{(calcite)} + H_2O + CO_2\ \text{(dissolved)} \rightleftharpoons Ca^{++} + 2HCO_3^-$$

These chemical reactions are natural processes. When ground water contains dissolved carbon dioxide, it will react with the carbonate minerals until the water is saturated. The ground water will carry the dissolved minerals as calcium (Ca^{++}), magnesium (Mg^{++}), and bicarbonate (HCO_3^-) ions. If the water becomes supersaturated with these ions, some of the calcium and bicarbonate ions will combine to precipitate calcite until balance is restored. Such precipitated calcite can be seen as stalactites in caves and as a white crust in water pipes.

Dolomite and calcite minerals are not evenly distributed throughout the carbonate rock, and the ratio of calcite to dolomite varies over small as well as large areas. Because calcite dissolves more easily than dolomite, rock with a high calcite to dolomite ratio is more readily removed and will generally develop more distinctive karst landforms and hydrology.

However, karst processes cannot be simply defined by the chemical composition of the rock and water. Many of the sinkholes in Olmsted County have developed in the Prairie du Chien Group, which is chiefly dolomite, rather than in the carbonates of the Platteville Formation and Galena Group. A few sinkholes have even formed in the St. Peter Sandstone, but are probably the result of cavities in the underlying Prairie du Chien Group. Adjacent areas with apparently similar geologic and hydrologic conditions have radically different sinkhole densities. Although the carbonate chemistry provides the basis for karst processes, many environmental conditions, such as rock structure, the nature of unconsolidated sediments, and climate, also affect karst development.

Ground water in karst aquifers flows more rapidly through large cavities than through sediment-filled joints and cracks. Karst ground water, like surface streams, both transports and deposits sediment depending on the flow rate, and thus allows cavities to open and close. If the rocks were not well jointed and passages interconnected, karst development would be very slow.

Dissolution of carbonate rocks is generally more rapid during humid periods of warm to temperate climates than during glacial climates (White, 1988). Hedges and Alexander (1985) have summarized the evidence that the Paleozoic bedrock of Olmsted County has undergone at least four major periods of karstification before the current era. Records of soil borings made for construction of Interstate Highway 90 and observations of sediments filling exposed joints and bedrock depressions document the formation of a karst as a result of intense weathering during a warm, humid climate prior to the Pleistocene. The pre-Pleistocene karst had an irregular bedrock surface with sinkhole spaces at intervals of tens to hundreds of feet.

During the Pleistocene several cycles of glaciation filled the karst depressions with residual material from the pre-Pleistocene bedrock dissolution and also with glacial sediments. The glacial episodes tended to smooth off the landscape. Karst erosion and stream processes during the temperate interglacial periods tended to reopen the depressions. The present interglacial period is once again a period of erosion which is increasing the topographic relief of the County.

CAVES

Dissolution of carbonate rock at depth produces cavities within the bedrock which commonly are partly filled with sediments carried into them by the ground water. Caves are cavities that have grown to human scale. Cave sediments generally are a combination of unconsolidated materials from the surface and the insoluble residue from dissolution of the carbonate bedrock (White, 1988).

The water flowing through caves may be slightly acid, particularly if the water has equilibrated with air rich in carbon dioxide, or it may be neutral if the water is saturated with bicarbonate, calcium, and magnesium ions. Dissolution or precipitation will occur, depending on the balance between the carbon dioxide and the carbonate ions.

Several small caves exist in Olmsted County. Figure 1 is a map of Mickey's Cave, the longest cave known in the county. Mickey's Cave is about 440 feet long and is developed in rocks near the top of the Prosser Limestone. It is a typical joint-controlled maze cave. Such caves are common in Galena Group rocks. The vast majority of the sinkholes in Olmsted County, however, do not appear to connect to any enterable cave passage below.

Although most of the caves are in the Galena and Prairie du Chien Groups, significant caves also exist in the St. Peter Sandstone. Figure 2 is a map of Troy Sink, a cave located mainly in the St. Peter Sandstone. These caves presumably result from the upward stoping of solution cavities in the underlying Shakopee Formation. Large cavities or voids, which do not currently connect to the surface, are a significant engineering problem in parts of Rochester and may be present in other, less developed areas in Olmsted County. Water-well contractors routinely intersect large cavities hundreds of feet below the surface while drilling wells in the carbonate bedrock.

SINKHOLES

Sinkholes occur in all of the bedrock units above the Jordan Sandstone in Olmsted County. The sinkholes range in size from less than 3 feet to more than 100 feet in diameter and from 1 foot to about 30 feet in depth. Most of them are 2 to 40 feet in diameter and 5 to 10 feet deep. Sinkholes are circular or elliptical at the land surface, and the walls range from nearly vertical to shallowly inclined. Most sinkholes in the county are cone-shaped depressions.

Many sinkholes formed catastrophically when the soil collapsed under its own weight. Most catastrophic sinkholes are initally cylindrical, and later become cone shaped as the vertical walls begin to erode. However, not all sinkholes in Olmsted County have formed catastrophically. Surface depressions, referred to as subsidence sinkholes, occur slowly as sediment subsides into enlarged joints. The rate of subsidence will be affected by the amount of sediment carried by water flowing toward the enlarged joints, both from the surface and through the unsaturated zone. In general if the rate of subsidence is rapid, the sinkhole will be cone or bowl shaped, and if it is slow, the depression will be shallow.

A sinkhole initiated by catastrophic collapse may periodically collapse again, or it may continue to grow by subsidence. Other sinkholes may begin with subsidence and later collapse catastrophically. Catastrophic and subsidence sinkholes are two end-members on a continuum of karst processes that result in sinkholes.

Once a sinkhole forms, it will grow as long as unconsolidated material continues to move through horizontal and vertical joints in the bedrock. The sinkhole will begin to fill if sediment transport into the depression exceeds sediment removal through joints in the bedrock. A sinkhole that has been filling may collapse again, if the rate of sediment removal increases or if the sediment input decreases.

Surface water tends to flow into the sinkhole, moving sediment deeper into the bedrock. Sediment transport is also affected by fluctuations in the water table. A high water table tends to support joint-filling sediments in position, but when the water table drops, sinkhole sediments move deeper into the bedrock. The rate of sediment transport through the sinkhole, the interaction between surface water and ground water, and the rate of bedrock dissolution determine whether the sinkhole is actively subsiding or passive. Each of these factors may change with time.

People have filled many sinkholes with unconsolidated materials to smooth the land surface. Most of these filled sinkholes have remained closed for the past 5 to 15 years, although some of them periodically collapse again. It is difficult to predict whether a sinkhole will remain closed, because it is not possible to measure all of the factors causing sinkhole collapses.

ENVIRONMENTAL IMPORTANCE OF KARST

Karst terrains are subject to several different types of environmental problems (Beck, 1984; NWWA, 1986; Beck and Wilson, 1987). Ground-water contamination is one of the major problems in Olmsted County's karst, as it is in most karst areas of the world. The funneling of surface contaminants into the ground water is increased by erosion around a sinkhole as it develops and forms a small surface drainage basin. Agricultural chemicals sprayed on fields may be dissolved in water or carried on sediment washing into the sinkhole, and move downward through joints into the aquifers. When waste products are thrown into sinkholes, any chemicals or bacteria from these products will also contaminate the ground water. About half of the sinkholes in Olmsted County have been improperly used for disposal of waste. These materials range from the relatively harmless to pesticide containers. Indicators of such ground-water contamination entering through sinkholes may be the high nitrate and coliform levels and the pesticides which have been observed by the Olmsted County Health Department, Minnesota Department of Health, and Minnesota Department of Agriculture in many Olmsted County wells that use karst aquifers, notably the Galena Group and the Prairie du Chien Group. Ground-water contaminants from urban and industrial sources also affect the quality of water in karst aquifers. In Olmsted County, nitrates, bacteria and other pollutants from closely spaced domestic drain fields, salt from road de-icing, and salt and other pollutants from waste-disposal spray fields are problems in urban areas.

The ground-water contamination problems associated with karst extend into regions without sinkholes and can influence water quality in springs and wells in noncarbonate aquifers. Hallberg and others (1983) and Libra and others (1984) have concluded that most of the ground-water contaminants in northeastern Iowa's karst region enter the aquifers through soil infiltration and not through direct runoff into sinkholes. Although similar studies have not been conducted in Olmsted County, the lack of surface streams in the upland dry valleys indicates that infiltration through relatively thin soils into the karst aquifers is probably a major source of ground-water recharge in Olmsted County. Recharge of the Jordan Sandstone (Plate 5) takes place through the Prairie du Chien Group in most of Olmsted County. Although the Jordan is not carbonate rock, the quality of the water currently in the Jordan was largely determined when that water passed through the overlying Prairie du Chien.

Other environmental problems created by sinkholes are physical. Sinkholes can cause rapid erosion by soil sliding into the hole. Soil loss removes farmland from production and thins the valuable topsoil. Potentially hazardous incidents have also occurred when new sinkholes opened catastrophically under farm equipment being driven over fields.

All types of facilities may be structurally damaged when a sinkhole opens. Home owners may experience economic losses from sinkholes collapsing near or under a house foundation, road, or sewer line. Water-retention facilities are highly susceptible to sinkhole collapse, inasmuch as these structures change the water saturation and lower the shear strength of the surficial materials (Aley and others, 1972). Sinkholes that develop under facilities storing potential ground-water contaminants will drain the pollutants into the ground water.

The rate of sinkhole formation in Olmsted County appears to have increased in the last few decades. Dalgleish and Alexander (1984a, b) found a similar result in Winona County. Of the 865 sinkholes inventoried, 59 appear to have formed in the last 6 years. At the present rate of about10 new sinkholes per year, all of the sinkholes in Olmsted County could have formed in the last 90 years. This is clearly not the case, because many of the sinkholes are more than 100 years old. Although the specific causes of sinkhole collapse in Olmsted County are uncertain, human activities elsewhere have significantly increased the rate of sinkhole formation (Aley and others, 1972).

Although data specific to Olmsted County are lacking, there is a growing national recognition that radon contamination of indoor air is a major long-term health hazard (BEIR IV, 1988). Webster and Crawford (1988) have recently argued that homes built in karst areas may be especially susceptible to radon contamination, and Lively and Ney (1987, 1988) have documented high levels of radon in Mystery Cave in Fillmore County. Radon contamination may well prove to be a significant problem for some dwellings built in karst regions like Olmsted County.

GENERAL CONCLUSIONS

The carbonate bedrock is the primary control on sinkhole formation. The distribution of sinkholes is strongly influenced by the presence or absence of at least 50 feet of surficial cover over the carbonate bedrock. Topographic relief, hydrologic gradient, and water table are secondary controls that vary in order of significance throughout the county.

Another factor which may be controlling sinkhole formation is the pre-Pleistocene karst, which developed during the warm, humid climate of the Tertiary. This old karst is called paleokarst. Many of the existing sinkholes probably have redeveloped on the sites of paleokarst sinkholes.

One of the major unanswered questions of southeastern Minnesota's karst geology is why adjacent areas having apparently identical geologic conditions commonly exhibit radically different sinkhole densities.

A sinkhole can form almost everywhere in Olmsted County. Although a sinkhole is more likely to form near existing sinkholes, Murphy's Law predicts that it will form in the least desirable place, i.e., under whatever you are trying to do!

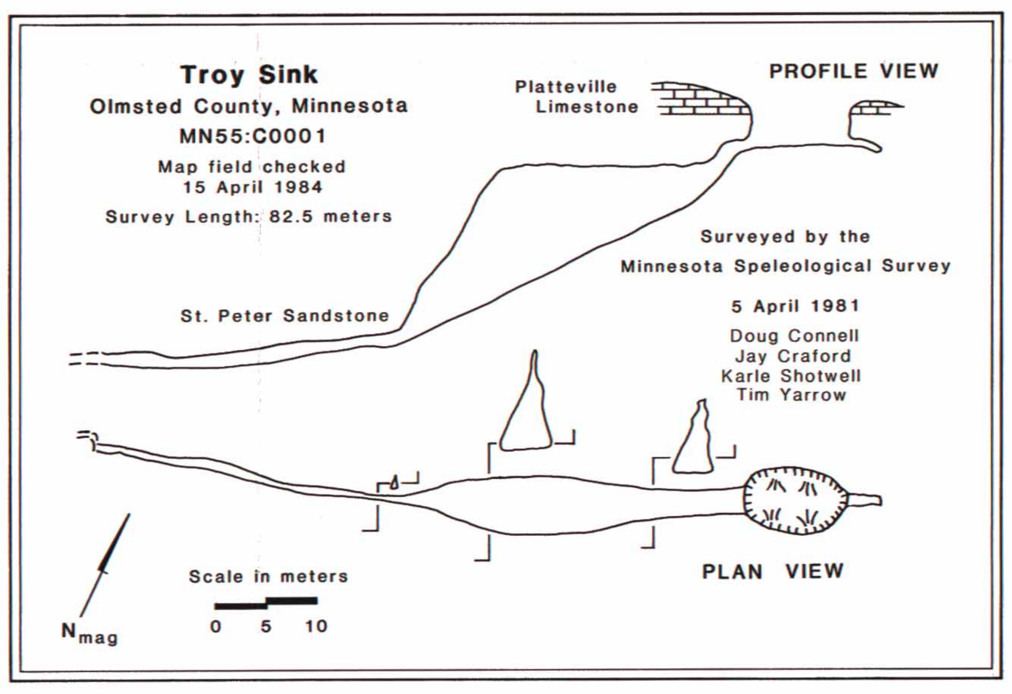

Figure 2. Plan and profile view of Troy Sink. This map is reproduced with permission of the Minnesota Speleological Society.

MAP SYMBOL

o Sinkhole

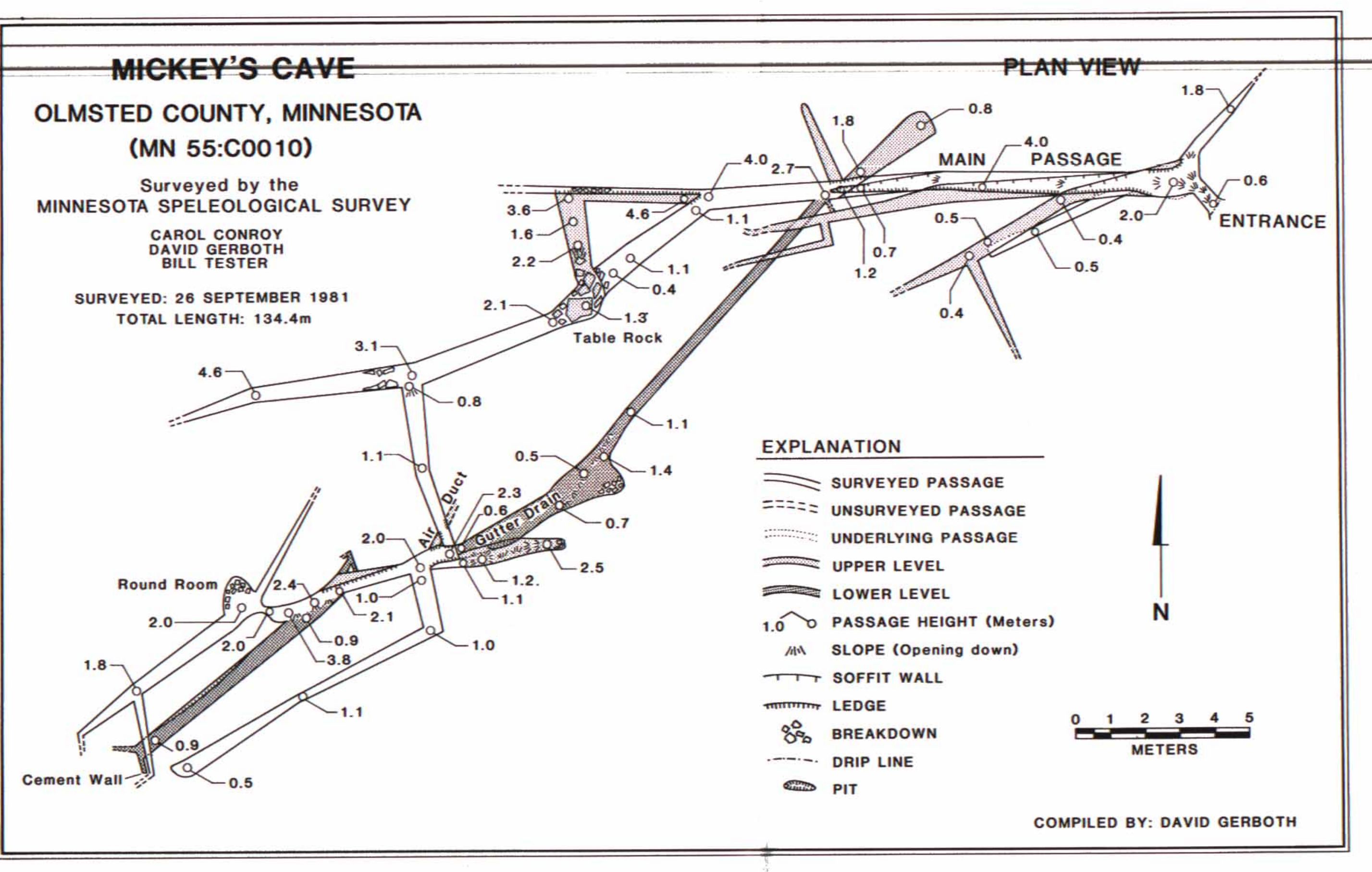

Figure 1. Map of Mickey's Cave. The cave was explored and mapped by members of the Minnesota Speleological Survey (MSS)—a nonprofit organization of cave explorers, which is not affiliated with the Minnesota Geological Survey. The map is reproduced with the permission of the MSS. Note that 1 meter is approximately 3.3 feet.

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