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THE ORIGIN AND MORPHOGENETIC SIGNIFICANCE OF PATTERNED GROUND IN THE SAGINAW LOWLAND OF MICHIGAN

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THE ORIGIN AND MORPHOGENETIC SIGNIFICANCE OF PATTERNED GROUND IN THE SAGINAW LOWLAND OF MICHIGAN

By

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ABSTRACT

THE ORIGIN AND MORPHOGENETIC SIGNIFICANCE OF PATTERNED GROUND IN THE SAGINAW LOWLAND OF MICHIGAN

By

David Paul Lusch

More than 350 mi^2 of patterned ground have been delimited in the Saginaw Lowland of east-central Michigan on the basis of the interpretation of aerial photography of varying scale, film type and date of acquisition. This phenomenon consists of an ordered network of broad, shallow troughs enclosing slightly higher centers. Individual forms range from circular features (79 feet in diameter) to elongated cells (1,289 x 480 feet). Most of the patterns, which can be classified as nonsorted nets, formed in somewhat poorly drained loam or silt loam drift on low-relief ($\leq$ 15 ft/mi^2) surfaces which slope less than 3%.

The morphostratigraphic relationships of the Saginaw patterned ground to the Port Huron Moraine and proglacial Lake Warren I suggest that the nets formed not earlier than 13,000 yrs B.P., but are probably younger than 12,730 yrs B.P. The lower elevational limit of the nets is coincident with the shoreline of proglacial Lake Elkton (Lundy) in both the horizontal and isostatically uplifted terrain, indicating that active pattern formation was contemporaneous with, and bounded by, Lake Elkton. Early Lake Algonquin, the next proglacial lake in the sequence, came into existence about 12,400 yrs B.P. and provides a minimum date for the cessation of active pattern growth.

The Saginaw patterned ground is interpreted to be the result of thermal contraction-cracking and ice wedge development in periglacial permafrost. An ice-wedge cast, underlying the mesh of one of the patterns, provided supporting evidence for this conclusion. This pseudomorph is composed of a well-sorted, medium sand surrounded by a sandy clay loam to clay loam till. The abrupt boundary and marked textural difference between these two sediments suggest that the sand was deposited from above into a pre-existing wedge-shaped void in the till.

Ice-wedge fossilization was rare in the Saginaw Lowland, however. The somewhat poorly drained, fine-textured drift on which the patterns occur must have been conducive to the formation of ice-rich permafrost. Upon thaw, this material would have been prone to liquefaction, thereby severely restricting the opportunity for the replacement of wedge ice with allochthonous sediments.

The nonsorted nets in the study area provide geomorphic evidence of at least local discontinuous permafrost conditions during a brief interval (350-600 years) of the Late Wisconsinan Substage. This morphogenetic conclusion implies a mean annual air temperature of -1° to -6°C in the Saginaw Lowland of Michigan during the waning Port Huron Stadial.

To Claudia, Peter and Ann

ACKNOWLEDGMENTS

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Finally, the essential contributions of my family to this endeavor must be recognized. The support, encouragement and understanding of my wife, Claudia, went far beyond the norm. Her acceptance of countless lonely evenings and weekends cannot be repaid; her love will always be treasured. My children, Peter and Ann, have had to sacrifice the fatherly attention they deserve. Their smiles and hugs at the end of a long day helped tremendously.

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CHAPTER I

INTRODUCTION

Background

Patterned ground is the general term used to describe any regolith surface which exhibits a discernible, more or less orderly and symmetrical micro-physiographic pattern (Brown and Kupsch, 1974). It was originally proposed by Washburn (1950) as the only satisfactory expression in English which embodies the meanings of a number of German words for the phenomenon, including Strukturboden (structured soil), Polygonboden (polygonal soil), Zellenboden (cellular soil), Spaltennetze (fracture nets), Netzrissboden (fracture-net soil), Wabenboden (honeycomb ground) and Rautenboden (rhomboid soil). Patterned ground is characteristic of, and best developed in, regions of intensive frost action (Flint, 1971; Embleton and King, 1975; French, 1976). It is not, however, restricted to these morphoclimatic areas and, as noted by Washburn (1956, 1970, 1973, 1980), may have a variety of origins; for instance, nonsorted polygons resulting from thermal contraction-cracking of permafrost on the arctic coastal plain of Alaska (Black, 1952) are nearly identical in size, shape and marking to desiccation-crack polygons on some of the playa surfaces in the Mojave Desert of California (Chico, 1968). Correctly interpreting the genesis of patterned ground, therefore, requires careful geomorphic analysis.

Patterned ground in Michigan was recognized more than a decade ago (Brunnschweiler, 1969), but has since received little attention from geomorphologists. Some of the patterns in southwestern Bay County and north-central Saginaw County were studied by Tillema (1972) who concluded that they were fossil ice-wedge polygons which formed in periglacial permafrost.

This study, however, is not fully convincing, both in the presentation of the field evidence for ice-wedge casts and in the discussion of criteria by which such relict structures can be identified (Johnsson, 1959; Black, 1976).

The location of the patterned ground in the glaciated terrain of the Saginaw Lowland suggests either a glacial or periglacial origin for this phenomenon. Although the Saginaw patterns are somewhat similar in appearance to certain types of ice-stagnation terrain, their morphometry and pedologic structure point toward a mode of origin determined by the presence of ice wedges in permafrost. It is known that during the waxing phase of the Wisconsinan glaciation, permafrost formed in front of the expanding ice sheet and may have persisted beneath the glacier in localized areas where subglacial temperatures were below 0°C (Péwé, 1973). As the continental ice mass waned, recently uncovered drift became perennially frozen and ice wedges formed in locales where especially rigorous conditions existed.

Although the frost-debris tundra zone[1] in the Midwest had a more restricted latitudinal extent than elsewhere (Brunnschweiler, 1962; 1964), the impact of the climatic conditions in this realm on Late Wisconsinan morphogenesis cannot be discounted. Paleobotanical evidence suggestive of this migrating tundra zone in Michigan is limited, but the overall paucity of organic remains associated with the interstadials following the Late Wisconsinan maximum (19,000-21,500 yrs B.P.) has been interpreted as an indication of cold, dry conditions which were too rigorous to allow plant migration from the south (Goldthwait, 1968; Wayne, 1968; Dreimanis, 1977).

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[1]This term, translated from the German Frostschuttzone, was suggested by Büdel (1951) to differentiate the cryomorphologically more active plantless tundra zone from the forest tundra zone along its equatorward margins.

At issue is the existence of a morphoclimatic zone fringing the waning continental ice sheet within which permafrost cracking and ice wedge development occurred. In a recent review article, Black (1976) critically evaluated numerous published reports of fossil ice-wedge casts and patterned ground in temperate North America. In most cases, he found that the data presented in these studies were inconclusive or misinterpreted and, as a result, an ice wedge origin for most of these features was rejected. It was also speculated in this review that the only favorable location for ice wedge development in the Great Lakes Region during the Late Wisconsinan was the large interlobate re-entrant in western Wisconsin (the so-called "Driftless Area"). Of particular relevance to the present study is a statement by the same author that ice-wedge casts were not to be expected inside of the Late Wisconsinan ice border in the United States, yet he cited two such occurrences (Black, 1965).

Indisputable evidence of Late Wisconsinan ice wedges and associated patterned ground have been reported from southwestern Ontario (Morgan, 1972; Greenhouse and Morgan, 1977). These features are especially germane because their appearance and form are very similar to the patterns in the Saginaw Lowland and they occupy a comparable morphostratigraphic position.

Statement of Problem

The Port Bruce glacial readvance in the eastern Great Lakes Region culminated about 14,000 yrs B.P. and tundra conditions probably existed in the periglacial zone at this time (Dreimanis, 1977). Within a relatively short time thereafter, the ice margin began to retreat rapidly, yet plant fossils from two sites of Mackinaw Interstadial age in Michigan document tundra conditions during this interval (Miller and Benninghoff, 1969; Burgis, 1970). The subsequent readvance during the Port Huron Stadial deposited tills which differ in composition and fabric from those of the preceeding Port Bruce Stadial, suggesting a rearrangement of the glacial flow patterns following the Mackinaw Interstadial (Dreimanis, 1977). These variations can be interpreted to indicate either a significant climatic change or alterations of the thermal-dynamic regime of the Laurentide ice sheet, but the fossil ice-wedge polygons in southwestern Ontario (Morgan, 1972; 1982) provide evidence of a substantial lowering of temperature.

This dissertation will focus on the origin and morphogenetic significance of patterned ground in the Saginaw Lowland of Michigan. In particular, the hypothesis that these features are fossil ice-wedge polygons resulting from permafrost cracking will be tested. Acceptance of this hypothesis is contingent on several factors. First, the morphometric attributes of the Saginaw patterns must be comparable to the geometry, mesh size and surficial marking of active, inactive or fossil ice-wedge polygons which have been reported elsewhere in North America and northern Eurasia. Second, the edaphic characteristics of the patterned terrain in the study area must be consistent with the textural and natural drainage conditions which are known to promote permafrost and ice wedge development. Lastly, fossil ice-wedge casts must be present underlying the mesh of the Saginaw patterns. Field criteria by which ice-wedge pseudomorphs can be identified have been reported by Johnsson (1959) and Black (1976) and will be utilized in this study.

Given the striking appearance of the Saginaw patterned ground and considering the paucity of geomorphic documentation of periglacial permafrost in the Great Lakes Region during the ice-marginal fluctuations of the Late Wisconsinan, the following research objectives were pursued and are discussed in the following chapters:

1) Documentation of the distribution of the patterned terrain in the Saginaw Lowland and analysis of its geomorphic and edaphic character;

2) Description of the morphostratigraphic relationships between the patterns and the known or re-interpreted glacial and glacio-lacustrine landform sequences in order to determine the time-stratigraphic position of the patterns;

3) Investigation of the geomorphic agents and associated processes which may have been active during pattern formation, to be accomplished through an analysis of data on the surface morphometry and subsurface structure of the patterns, as well as a critical evaluation of theories suggesting alternative origins for such features; and

4) Discussion of the paleoenvironmental significance of the Saginaw patterned ground, with special emphasis on the reconstruction of the thermal regime during and immediately after ice retreat in the study area.

As mentioned earlier, patterned ground is a general term for a variety of geometrically arranged surface phenomena which may result from numerous processes. Although this study will specifically test the hypothesis that the patterns in the Saginaw Bay area resulted from ice wedge development in permafrost, other mechanisms which are reported in the literature to form similar features will also be given full consideration. Conclusions concerning the origin of the patterned ground in the Saginaw Lowland of Michigan will allow their morphogenetic significance to be assessed in both the local and regional context and should contribute to a better understanding of the Late Wisconsinan environment in east-central Michigan.

Methods and Techniques

The interpretation of aerial photographs was a major research technique used in this study. Mapping the distribution and extent of the patterned ground in the Saginaw Lowland, as well as studying its morphometric characteristics, is only feasible by analyzing airphotos because, in spite of their sharp definition in the aerial view, these features are virtually imperceptible to the ground-level observer. During the preliminary phase of this investigation, inspection of various types and scales of aerial imagery of the counties bordering Saginaw Bay revealed that the patterns are well defined on even small-scale photography, particularly if it was acquired in the spring when soil moisture variations in the barren fields accentuate the network mesh.

Small-scale, color infrared (CIR) imagery acquired by NASA in the spring of 1975[2] was very useful for delimiting the areal extent of the patterned ground, but detailed analysis of individual patterns was more accurately accomplished from larger-scale photography, such as the 1:24,000 CIR photos from the Michigan Department of Natural Resources, or the county coverage from the Agricultural Stabilization and Conservation Service (A.S.C.S.).

Since agricultural activities and other changes in land cover can mask the patterned ground on airphotos, a multitemporal analysis was conducted with black-and-white panchromatic imagery acquired for the A.S.C.S. in 1955, 1963, 1969 and 1970. Both individual 9" x 9" prints and county photomosaics were used to map the areal limits of the patterns. In total, aerial photography from six different acquisition dates spanning 23 years was interpreted, providing the highest possible accuracy for

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[2]NASA-JSC Mission 309. All of the high-altitude imagery of Michigan acquired by NASA's Manned Spaceflight Center and used in this study is archived at the Center for Remote Sensing, Michigan State University.

visual pattern delimitation.

Areas of especially prominent patterns in the Saginaw Lowland were delineated from 1:120,000 CIR aerial photographs. Compared to other available imagery of the study area, these small-scale photos revealed the patterns remarkably well, probably because they were acquired the day after the Saginaw Valley received an average of 0.32" of precipitation. In addition, this photo mission provided total coverage of the study area for the same day on a consistent film type and photo scale.

In order to recognize the morphostratigraphic context of the patterns, and as a means of establishing their relative age, the boundaries of the significant ice-marginal landforms and the locations of several proglacial lake shorelines had to be determined. Previous delineations of these surface formations were consulted (Leverett and Taylor, 1915; Martin, 1955), but it was necessary to redefine some of these features. These reinterpretations were accomplished by the combined analyses of aerial photographs, topographic maps and soil surveys coupled with field verification.

Special emphasis was placed on topographic profiles constructed across the previously delineated trends of the moraines in the study area because such landforms are defined primarily on the basis of their constructional topography (American Geological Institute, 1962). These profiles were compiled at a scale of 1:24,000 from U.S. Geological Survey topographic quadrangles which have a contour interval of 5 ft. Vertical exaggerations of either 40 or 50 times were chosen according to the amount of local relief present. The profile transects were extended several miles beyond the previously mapped boundaries of the moraines in order to assess the accuracy of these delimitations. Since the Port Huron drift is known to be fine-textured (Leverett and Taylor, 1915), soil data aided the interpretation of dune complexes, beach ridges and lacustrine bars and spits whose topographic expression, in some instances, could be confused with morainic terrain.

The shorelines of selected proglacial lakes were mapped by combining the interpretations of aerial imagery with pedologic and topographic data from existing maps. Many of these littoral features, both erosional and depositional, are obvious on medium and small-scale aerial photography as discontinuous, curvilinear trends in the landscape. These were mapped on acetate photo-overlays and subsequently transferred to 1/2":1 mile county base maps. Shore features in the zone of horizontality for Lakes Grassmere and Elkton were identified on the basis of their topographic elevation (640 ft. and 620 ft., respectively); the beaches were mapped across the uplifted zone north of the zero isobase by means of their spatial continuity and relative position. Because the study area is north of the Warren hinge line, all of the shorezone features associated with Lake Warren have been uplifted relative to its horizontal elevation of 680 ft. Nevertheless, the conspicuous shoreline along the proximal flank of the Port Huron Moraine in Tuscola County has been accepted as the Warren beach in previous studies (Leverett and Taylor, 1915; Martin, 1955) and this served as the point of reference for the mapping of the remainder of the Warren shore.

Although airphotos are used as a mapping base for modern soil surveys, the patterned ground in the Saginaw Lowland has not been recognized in these reports primarily because of the larger size of the soil mapping units compared to the pattern mesh and due to the fact that the patterns are not associated with a single soil series. Nevertheless, soil maps do provide valuable information on the dominant soil texture and natural drainage conditions characteristic of the patterned terrain. Other edaphic data essential to this research, such as evidence of subsurface soil structures or textural discontinuities underlying the surface patterns, were gathered from on-site field examinations. Most of the arable land in the study area is drained by road-side ditches and more than 100 miles of these drains, many of which expose five or six feet of drift, were inspected in the field. Sites where a pattern mesh intersected a ditch, as located by airphoto interpretation, were given special scrutiny in an effort to discern any sedimentological manifestations of the surface pattern.

At the Bridgeport site, five paired samples of the material in a soil wedge and the adjacent host regolith, each weighing about 200g, were extracted from the cleaned face of a drainage ditch exposure at depths of 0.2m, 0.55m, 0.8m, 1.1m and 1.4m. These sediments were subjected to particle size analyses using standard sieve and hydrometer techniques. As a means of assessing the three-dimensional character of the soil wedge, electrical resistivity surveys[3] were conducted. This geophysical technique has been reported to be useful for mapping patterned ground (Greenhouse and Morgan, 1977). The resistivity transects at the Bridgeport site utilized a Wenner probe configuration with 0.5m electrode spacings in order to concentrate the measurements in the upper 1.5m of regolith which contained the bulk of the soil wedge.

Due to the lack of other exposures, it was necessary to excavate three pits at the Lawndale site. The central and eastern excavations were approximately 2.5 x 3 ft., while the western pit was about 3 x 5 ft. All were dug to a depth of 6 ft. and their long axes were oriented east-west, transverse to the local trend of a prominent mesh zone. An electrical resistivity survey was conducted along a west-to-east transect

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[3]Appendix B describes the electrical resistivity surveying technique and illustrates how resistivity anomalies can be detected.

immediately north of these pits. The Wenner array configuration was also used at this site, but the electrodes were spaced only 14" apart in order to provide maximum resolution of subsurface resistivity anomalies in the upper 3.5 ft. of the regolith. Samples from the C horizons of the two-storied soils exposed in these excavations were also subjected to particle size analyses. Other edaphic data, particularly dominant profile texture, were collected from 25 auger borings which sampled the cell mesh to a depth of 5 ft. These auger sites were spaced at approximately 50 ft. intervals, except where observed changes in surface texture or color suggested that additional samples were necessary.

An analysis of the morphometry of the Saginaw patterns was conducted using photometric techniques. The lengths of the major (a) and minor (c) axes of 200 selected patterns in the study area were measured to the nearest 0.1mm on 1:60,000 CIR imagery. The average scale of each photo was calculated with reference to U.S. Geological Survey 7.5' topographic maps. These airphotos were utilized in an effort to standardize the analysis of the patterns from synoptic imagery which was acquired under nearly constant conditions on the same day.

The local relief of the patterned terrain was determined by calculating the arithmetic difference between the highest and lowest contour lines in each survey section as shown on U.S. Geological Survey 7.5' topographic maps. Since the contour interval on these quadrangles is 5 ft., these data have an inherent precision of $\pm$ 10 ft. Additionally, the areal unit of measure, nominally one square mile, varies somewhat due to imperfections in the U.S. Public Land Survey System.

CHAPTER II

LATE WISCONSINAN GEOMORPHOLOGY OF THE SAGINAW LOWLAND

Introduction

The reticulate network of patterned ground in the Saginaw Lowland which is the focus of this research occurs within a broadly arcuate tract across parts of Bay, Midland, Saginaw and Tuscola counties. The study area is part of the Saginaw Lake-Border Plain physiographic region of the state which is, in general, bounded by the shoreline of Lake Saginaw, the highest Late Wisconsinan proglacial lake, and the present shore (Brunnschweiler and Lusch, 1977). In order to correctly interpret the significance of the patterned ground, its geomorphic context, particularly with respect to the major glacial and glaciolacustrine landforms, must be established.

Moraine Boundary Mapping

The Saginaw Lowland contains a large segment of the Port Huron Moraine which, as preliminary investigations (Lusch, 1977) suggest, is spatially related to the distribution of the patterned ground. This hypothesis prompted a re-examination of the extent of the Port Huron and Bay City moraines in the study area. Previous attempts to delineate the moraines in this part of Michigan are limited to the reconnaissance mapping of Leverett and Taylor (1915) and several manuscript maps compiled at some later date by Leverett. The most recent graphic summary of these previous investigations is the "Surface Formations" map by Martin (1955) which depicts these moraines as shown in Figure 1.

Little is known about the specific criteria and methods used by Leverett and Taylor to delineate these ice-marginal landforms, but they were unable to utilize aerial photographs and detailed soils and

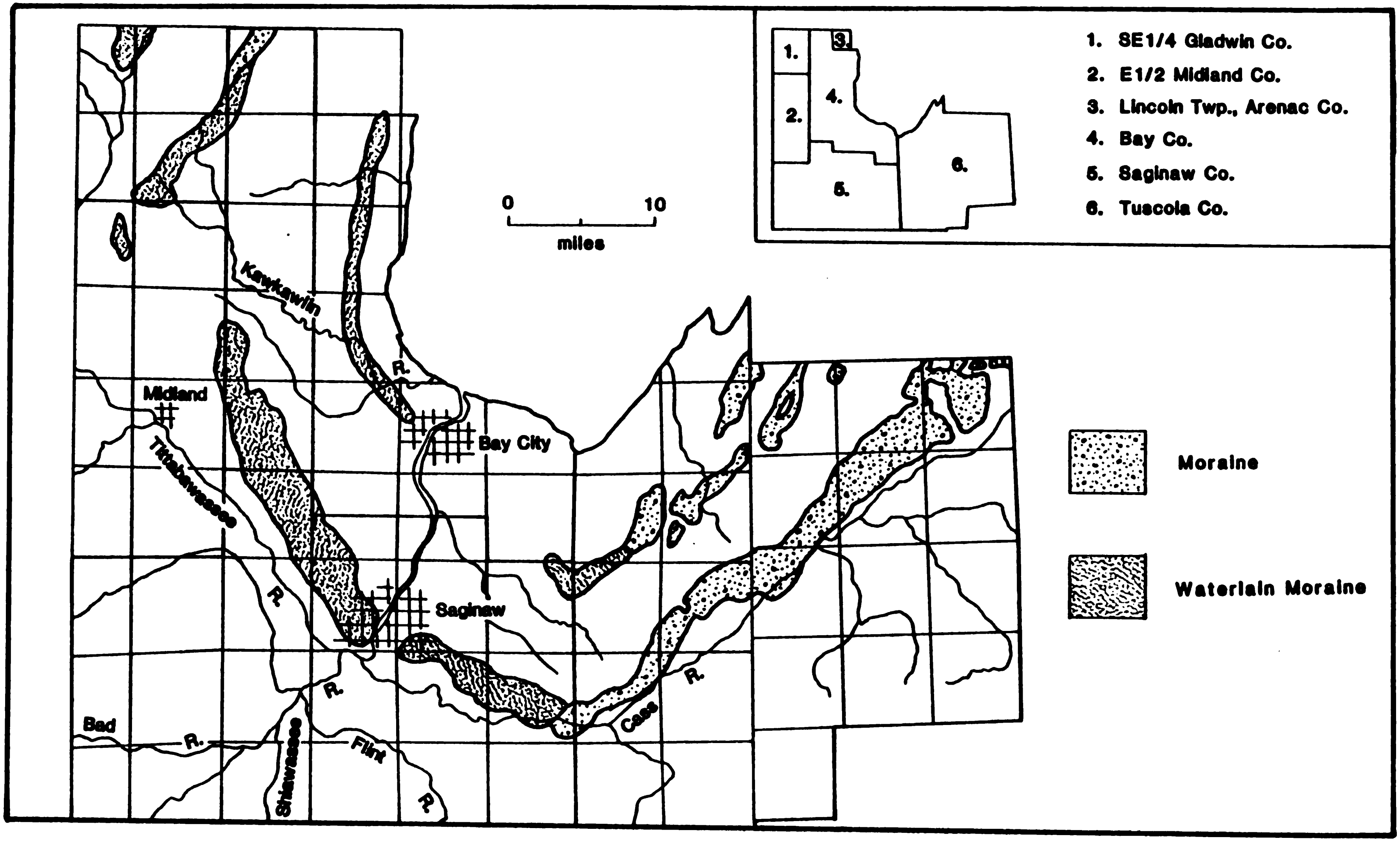

Figure 1. Extent and classification of the Port Huron Moraine in the study area, as shown by Martin, 1955.

topographic maps since these were unavailable at the time of their work. Differences, perhaps resulting from the lack of these detailed data sources, are apparent between the present interpretation (Figure 2) and Martin's 1955 map. Most notably, no evidence could be found to support the delineation of the Bay City Moraine proximal to the Port Huron system in the study area. The only conspicuous, positive topographic feature in the vicinity of this "moraine" in Bay County is the fairly continuous Nipissing beach ridge (Figure 3). In Tuscola County, the "Bay City Moraine" appears to correspond to a rather complex series of discontinuous beach ridges associated with proglacial Lake Grassmere and Lake Elkton (Figure 4). The location of these topographic transects are shown in Figure 5.

With respect to the general trend of the Port Huron Moraine across the study area, the present delineation and previous maps agree very well. There are, nevertheless, several places where major differences in the mapped extent of the moraine are obvious (Figure 6). The first of these is in the vicinity of the Saginaw-Tuscola county line in T. 11 N., R. 6 and 7 E., and T. 12 N., R. 7 E. Here the present interpretation, primarily on the basis of topographic data (Figure 7), established the proximal margin of the moraine several miles north of the previously accepted boundary. The extent of waterlain[1] moraine in this area has also

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[1]In a recent review of waterlain tills, Dreimanis (1979) concluded that tremendous confusion exists regarding the terminology used to describe these sediments. He agreed with Francis (1975) who pointed out that "waterlain" (i.e., lying in water) was linguistically more appropriate in this context than the often-used term "waterlaid" which means laid down by water. Consequently, Dreimanis (1979: 167) modified his earlier definition of "waterlaid" till (Dreimanis, 1969) to read, "Waterlain till: Glacial drift deposited as till in glaciolacustrine, glaciomarine or glaciofluvial environments." It seems reasonable to adopt a similar terminology for landforms which were emplaced in an aquatic environment, as well. In this report, the term "waterlain" moraine describes a type of moraine or a moraine segment which was deposited along an ice margin standing in proglacial meltwater or which was subsequently modified by glaciolacustrine processes.

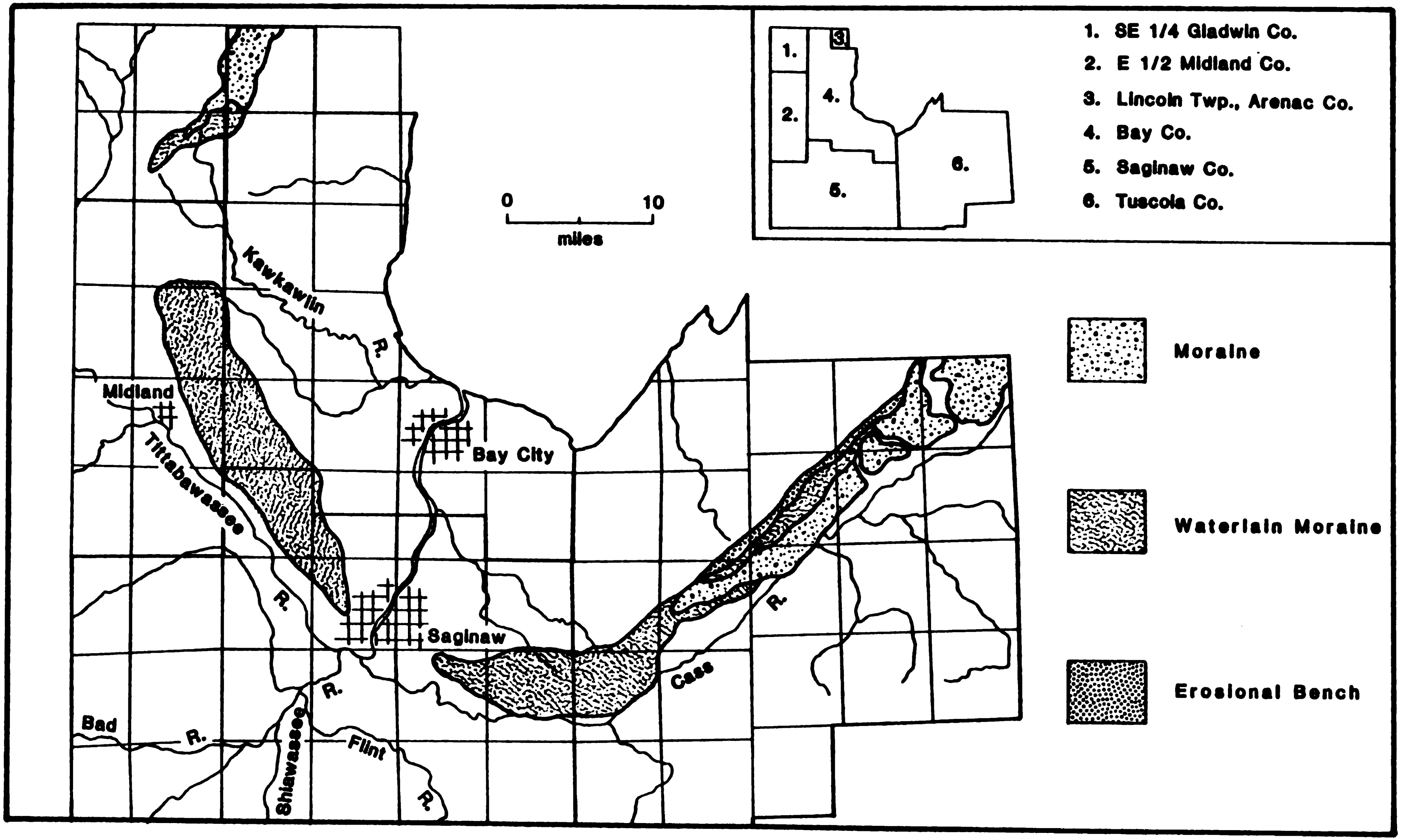


Figure 2. Revised extent and classification of the Port Huron Moraine in the study area.

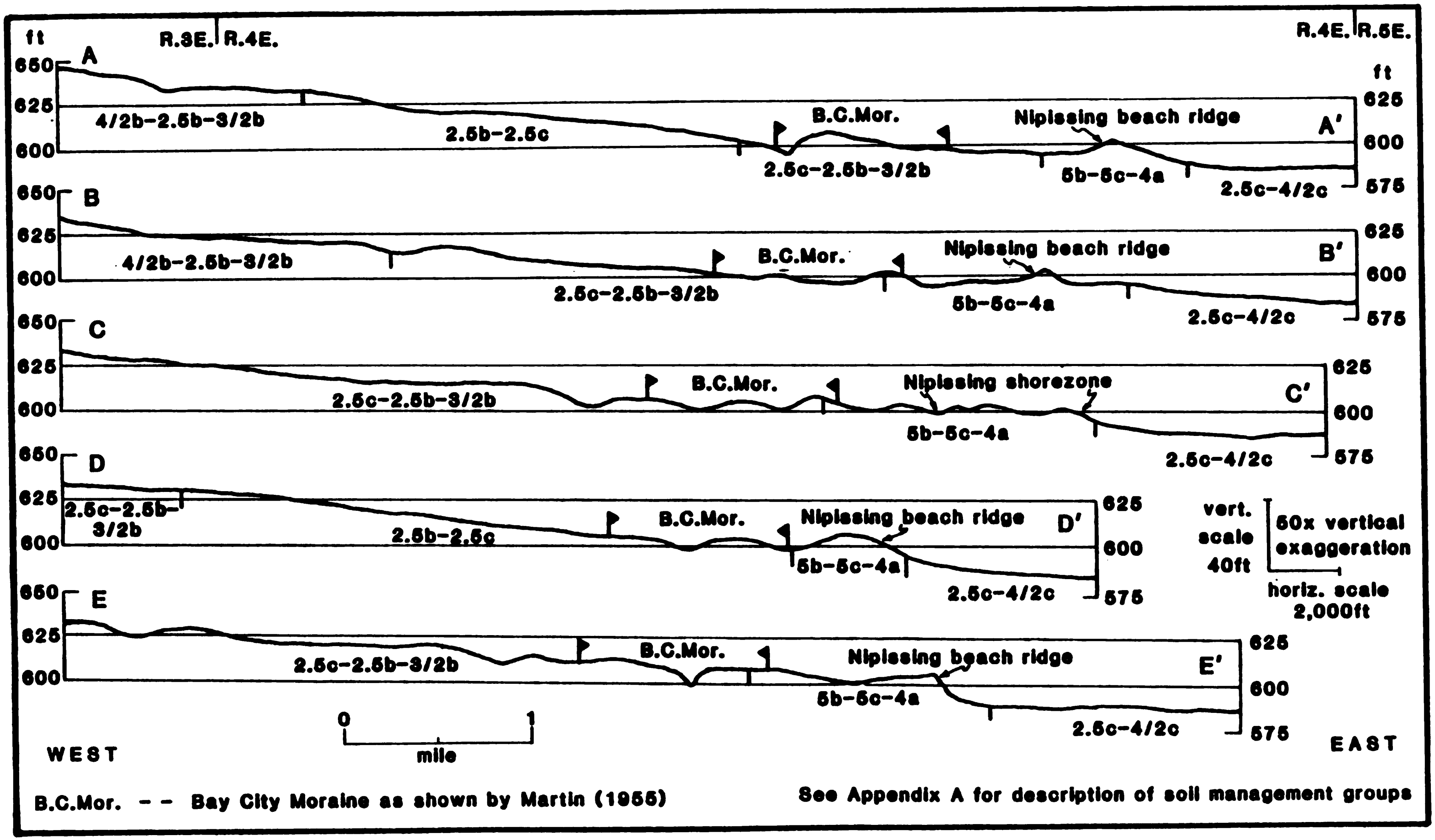


Figure 3. Topographic profiles and soil types across the "Bay City Moraine" in north-central Bay County.

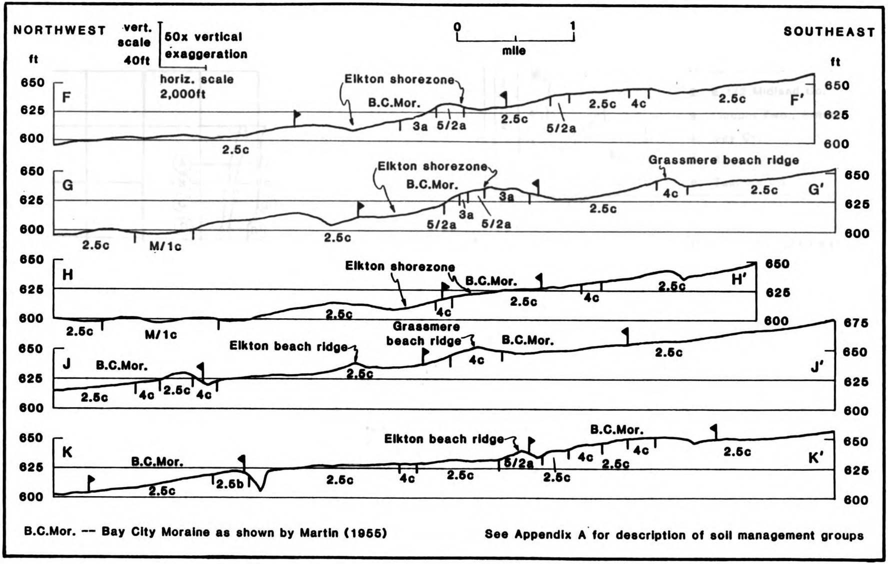


Figure 4. Topographic profiles and soil types across the "Bay City Moraine" in Tuscola County,

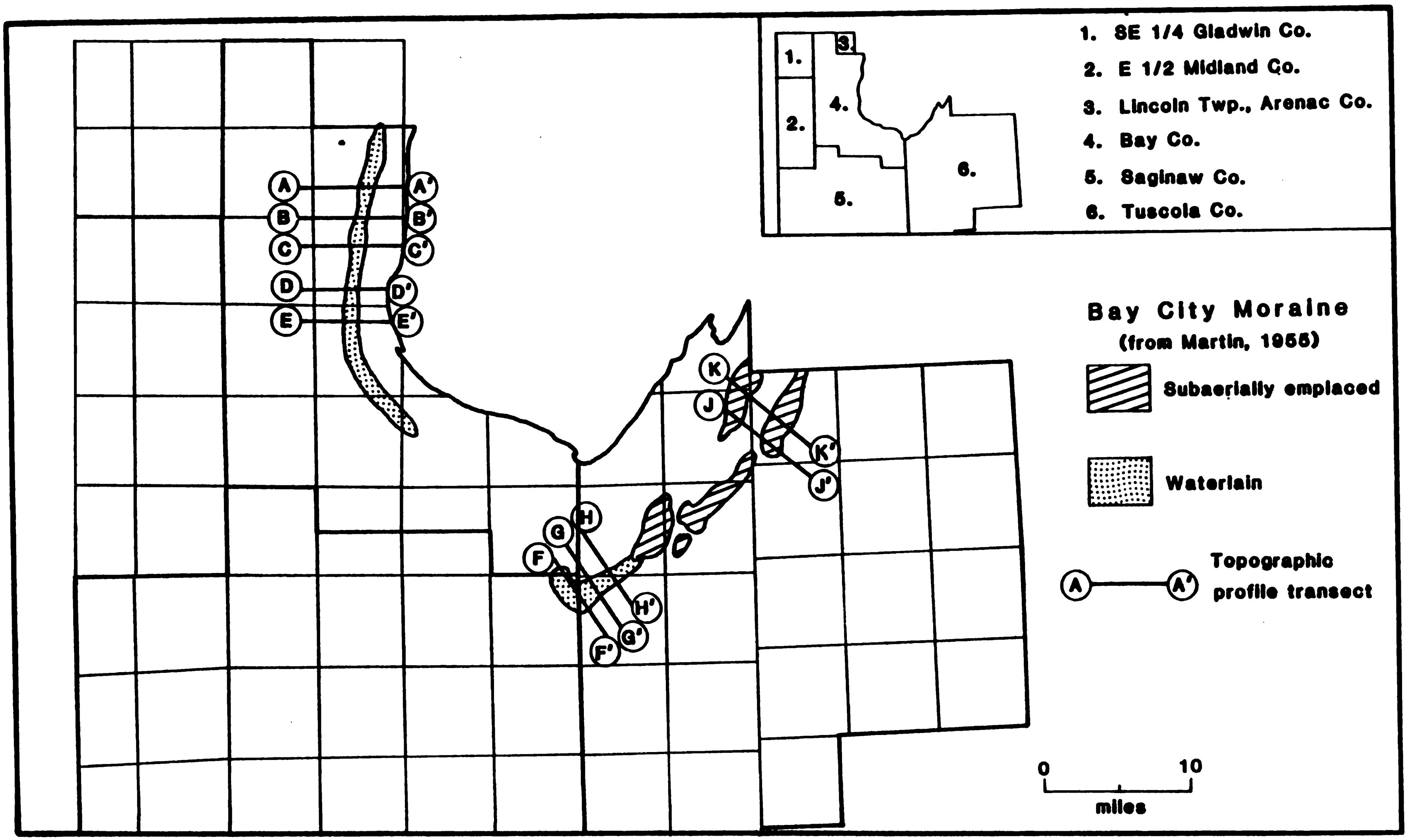


Figure 5. Locations of the topographic profiles shown in Figures 3 and 4.

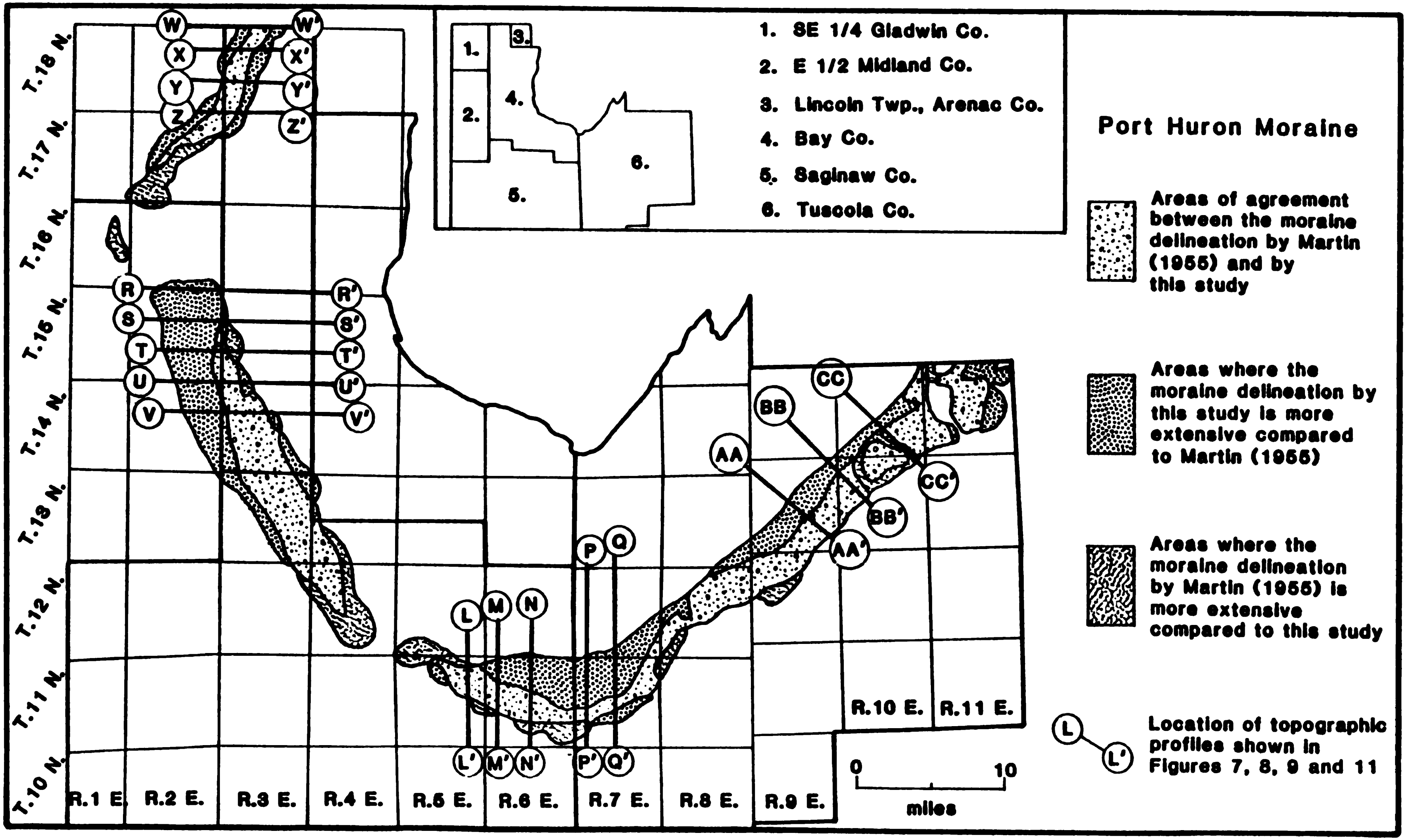


Figure 6. Comparison between the revised delineation of the Port Huron Moraine and the boundaries shown by Martin, 1955.

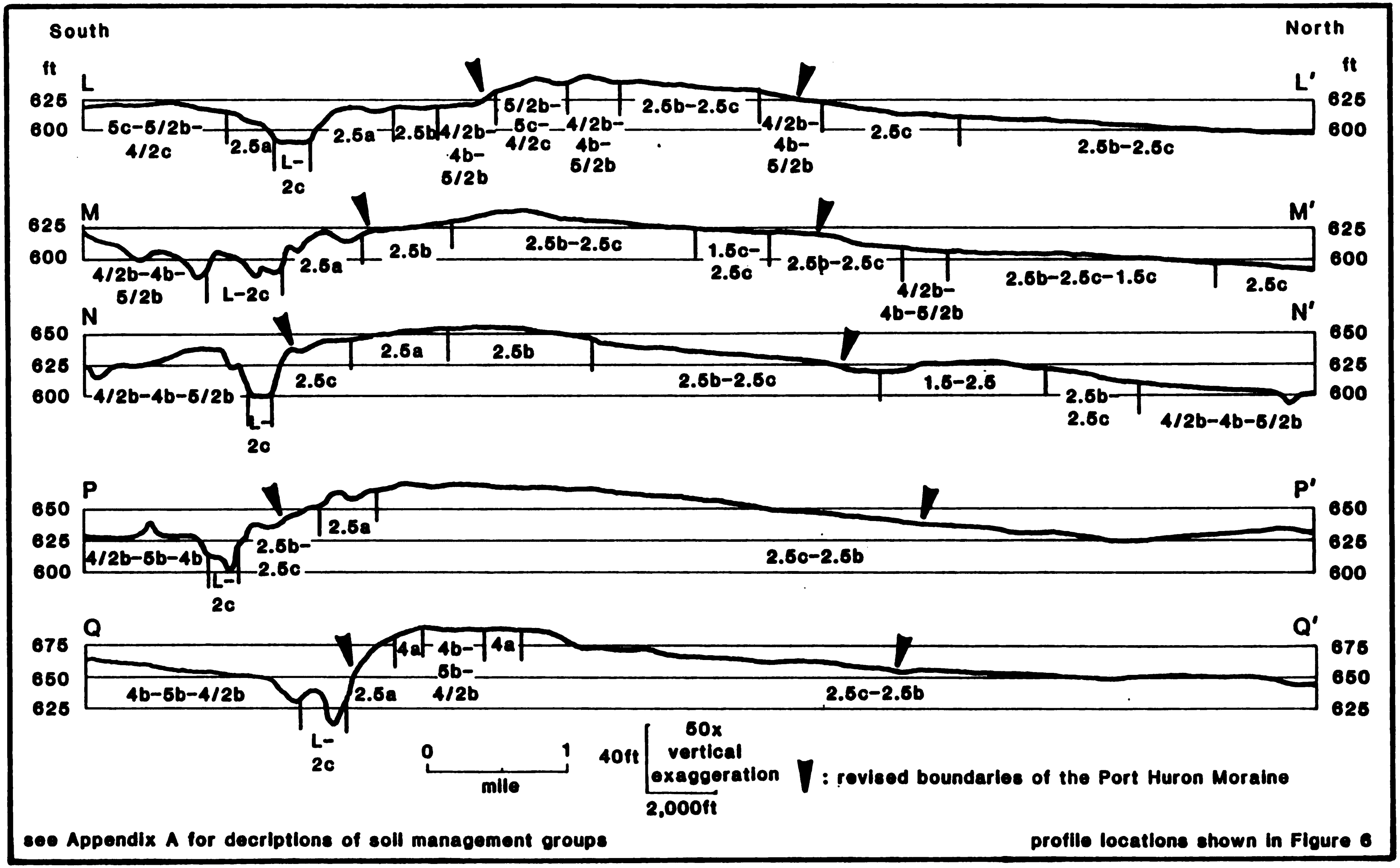


Figure 7. Topographic profiles across the Port Huron Moraine in western Tuscola County and eastern Saginaw County

been changed in that all of the moraine below the Warren shoreline (elevation 700 feet), which occurs one mile northwest of Vassar, is interpreted as having been deposited in standing water. In Tuscola County, the portions of the Port Huron Moraine which sustained little modification by lacustrine processes exhibit strong local relief and surficial soil mottling and tend to be naturally well drained. As observed on color infrared airphotos (Plate I), the bright, more well-drained soils of the subaerially emplaced moraine contrast vividly with the darker, more poorly-drained soils of the segment modified by lacustrine action. Additionally, the surficial mottling west of (below) the Warren shorezone tends to be subdued, providing corroborative evidence for the waterlain character of this section of the moraine. No evidence was found to support the waterlain moraine boundary in the vicinity of Frankenmuth as shown on Martin's (1955) map.

The differences in the extent of the moraine in north-central Tuscola County shown in Figure 6 are the result of a re-interpretation of the waterlain portions of the Port Huron Moraine which will be discussed more fully in a later section. The platform on the northwestern flank of the moraine (Figure 8) was previously delineated as lake plain (inundated till plain), but topographic data suggest that it may in fact be part of the moraine. This area would certainly have been inundated by Lake Saginaw during its initial formation and subsequently was subjected to both fluvial and lacustrine erosion.

A third locality where major differences in the interpretation of the glacial morphology can be seen is along the eastern border of Midland County. Topographic data for this area indicate that the Port Huron Moraine extends westward into Midland County (Ts. 14 and 15 N., R. 2 E.) farther than previously recognized (Figure 9). Although the distal margin

(NASA-JSC 309-21-102; May 13, 1975)

Plate I. High-altitude, color-infrared airphoto of the Vassar, Michigan area showing the well-drained soils (white to light cyan tones) associated with the Port Huron Moraine.

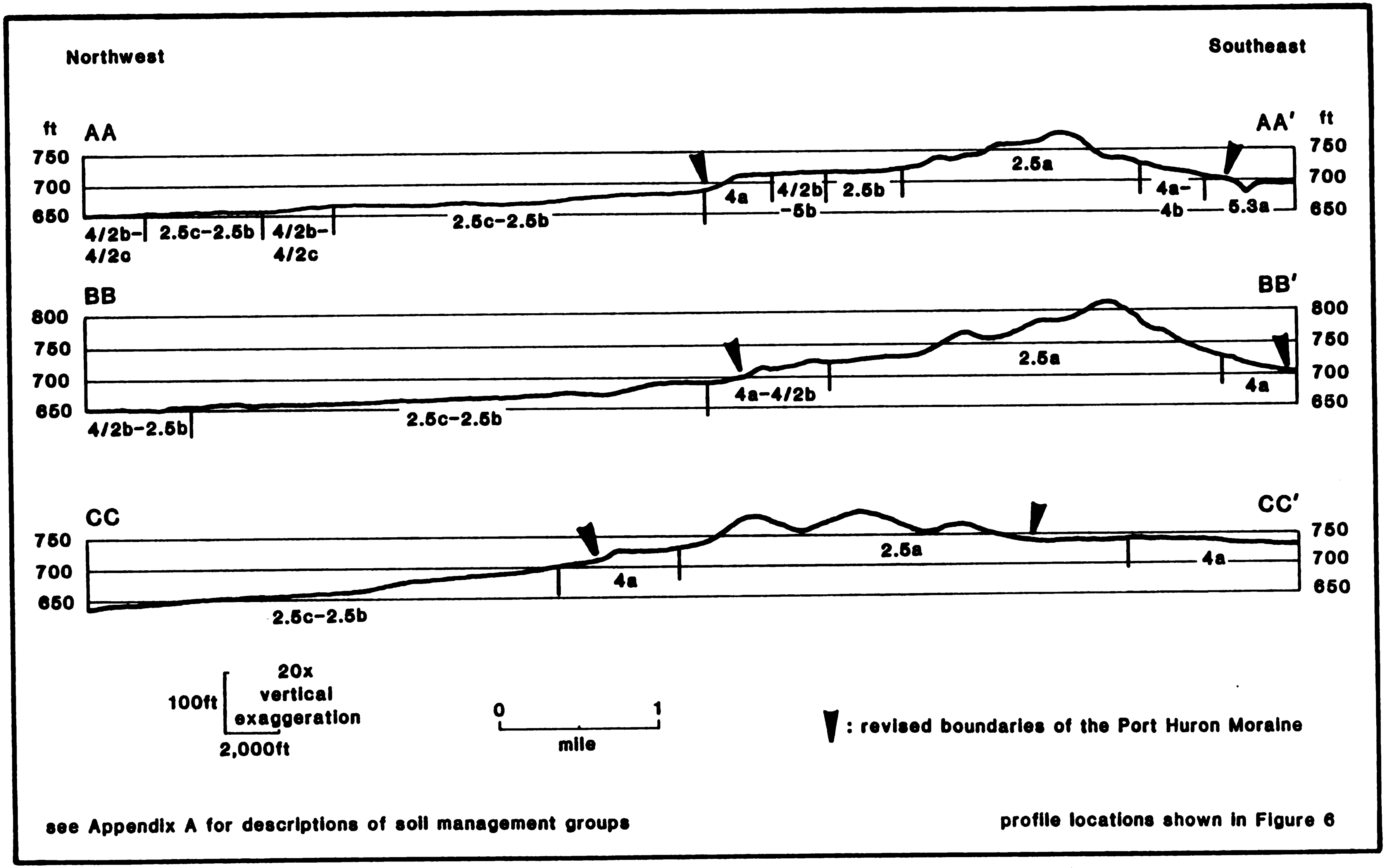


Figure 8. Topographic profiles across the Port Huron Moraine in northeastern Tuscola County.

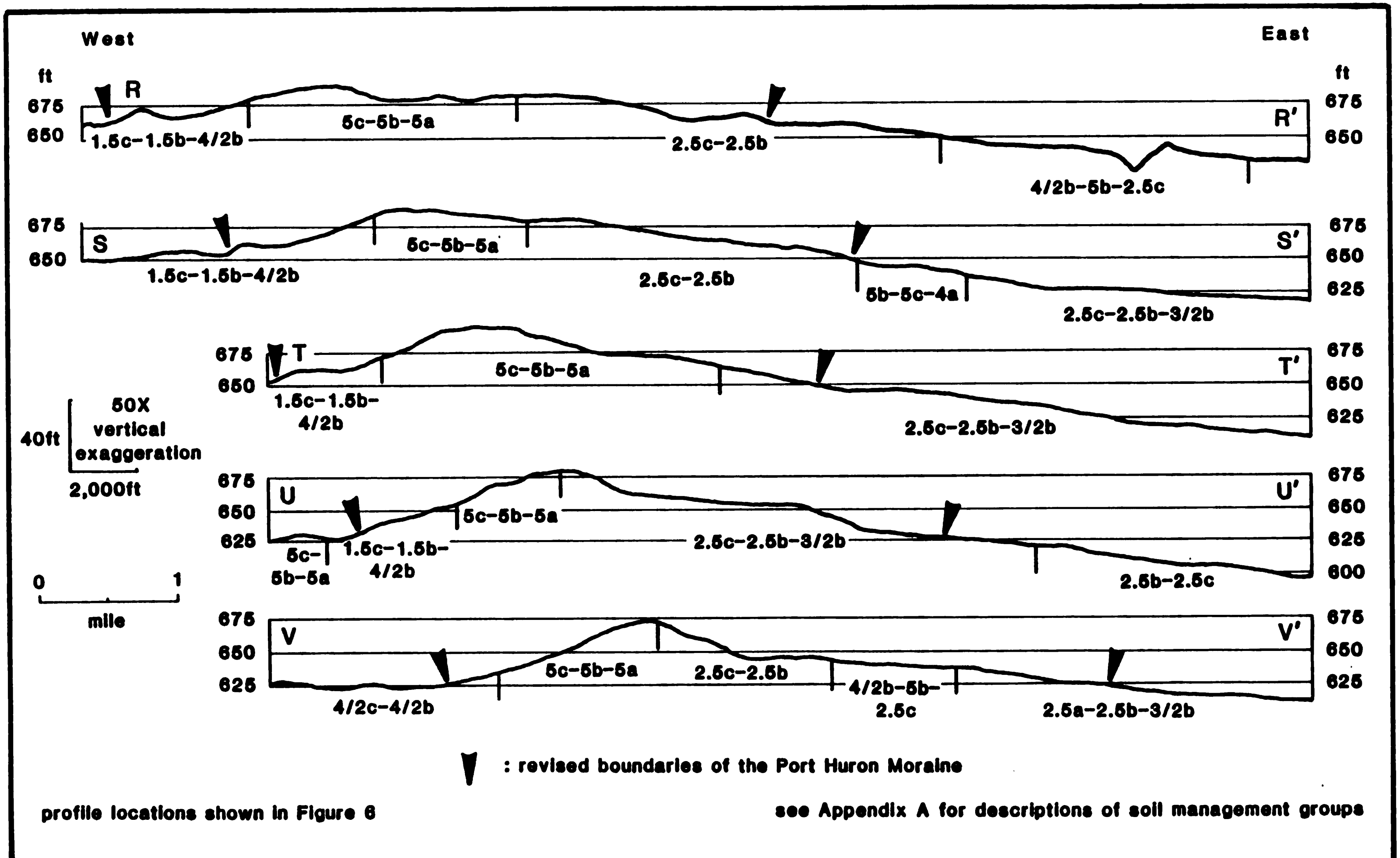


Figure 9. Topographic profiles across the Port Huron Moraine in Larkin and Midland townships, Midland County and Beaver and Williams townships, Bay County.

of the moraine in this region is obscured by sand dunes (Figure 10 and Plate II), published pedologic information, to be discussed later, corroborates the more westerly position of this moraine border.

Topography of the Port Huron Moraine

The Port Huron Moraine exhibits two distinct topographic expressions in the Saginaw Lowland. Across most of Bay, Midland and Saginaw counties, where the moraine was waterlain, it has a very subtle topographic form, with gentle slopes and low relief. In northernmost Bay County and in Tuscola County east of Vassar, on the other hand, the moraine becomes much more pronounced and, in general, local relief along its trend increases to the north and northeast.

In Gibson Township (T. 18 N., R. 3 E.), Bay County, the Port Huron Moraine attains an elevation of over 820 feet, rising some 50 to 70 feet above the surrounding countryside (Figure 11). This three-mile-wide section of the moraine is quite rugged with local relief averaging 45-50 ft/mi^2 and occasionally becoming as much as 85 ft/mi^2. Along the southern fringe of this hummocky moraine is a narrow (1-2.5 mi.) lacustrine-modified morainic zone which is only 5-15 feet above the adjacent landscape and has 20-25 feet of local relief per section.

The large morainic segment in eastern Midland, southwestern Bay and northwestern Saginaw counties, interpreted as being entirely waterlain, is 2.5-6 miles wide and has a relatively smooth and regular proximal slope. Its crest decreases in elevation toward the southeast, from 690-695 feet in Larkin Township (T. 15 N., R. 2 E.), Midland County to 615 feet in Saginaw Township (T. 12 N., R. 5 E.), Saginaw County. As mentioned earlier, the distal slope of this part of the Port Huron Moraine is covered in many places with sand dunes and these eolian landforms

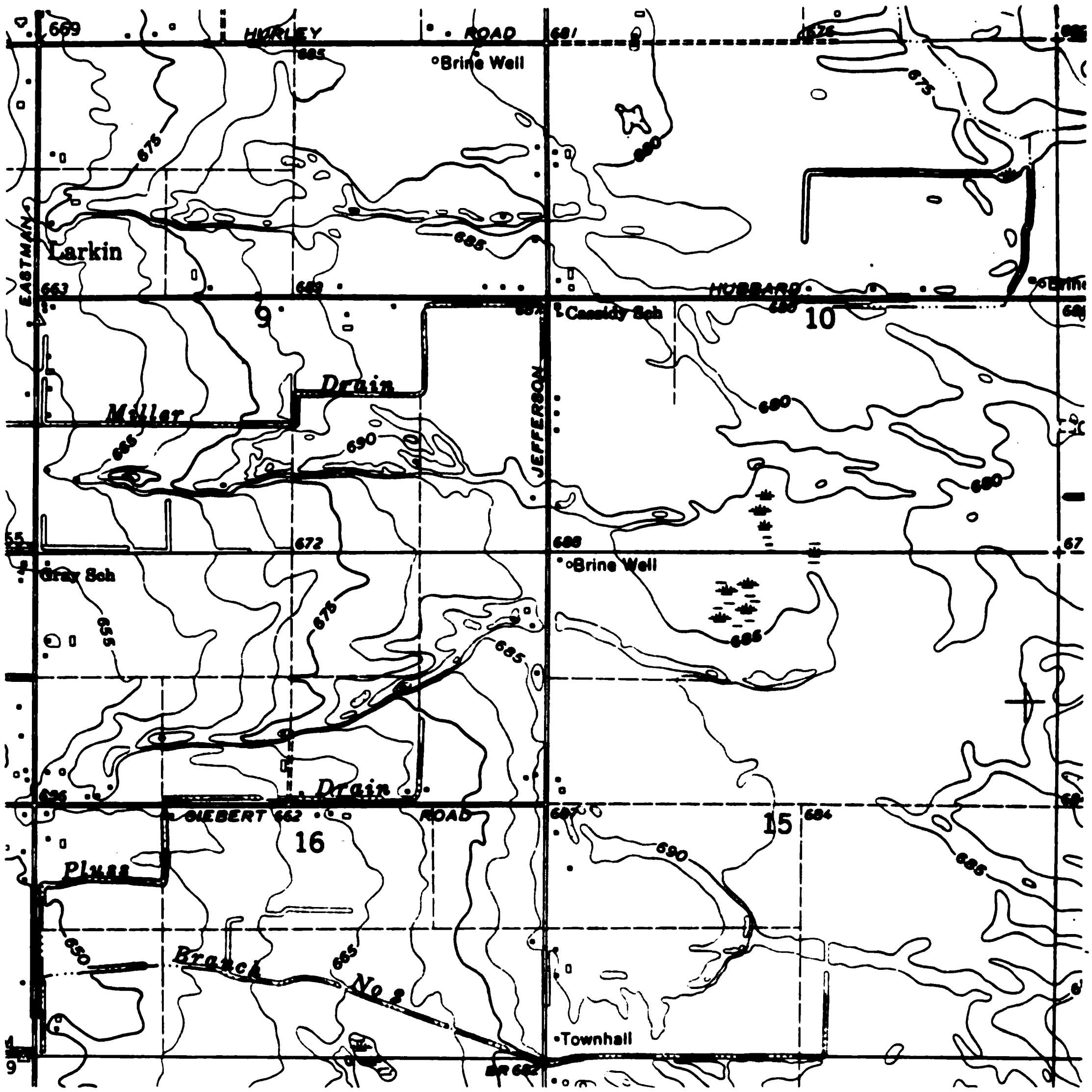
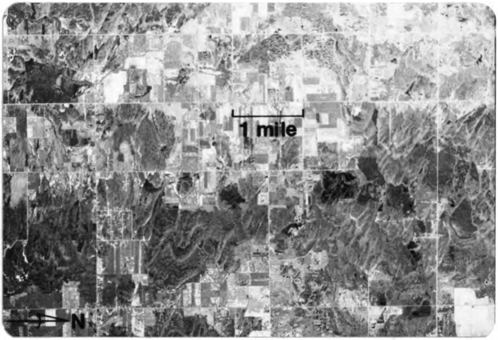


Figure 10. Portion of the Midland North 7.5-minute topographic quadrangle, showing the sand dunes along the distal slope of the Port Huron Moraine in central Larkin Twp., Midland County.



(NASA-JSC 309-21-67; May 13, 1975; Original in color)

Plate II. High-altitude aerial photograph of the sand dunes on the distal slope of the Port Huron Moraine in eastern Midland County.

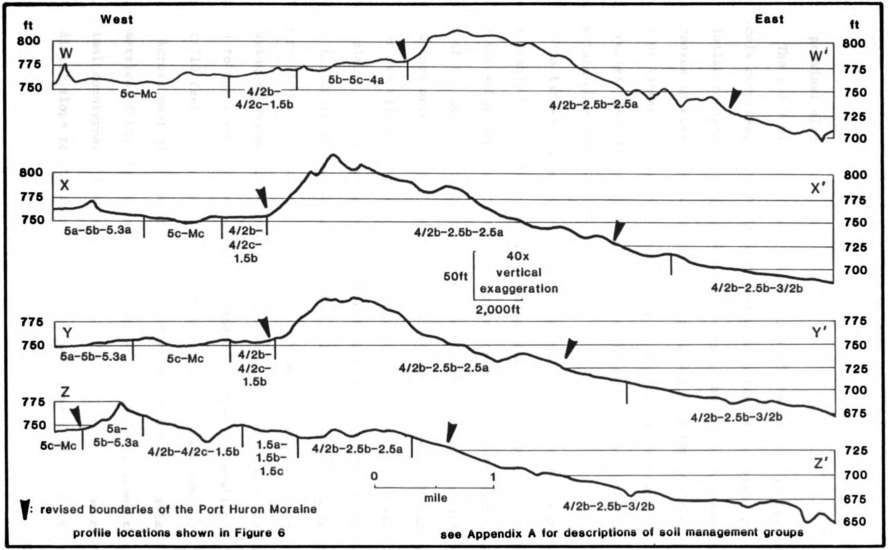


Figure 11. Topographic profiles across the Port Huron Moraine in Grim Township, Gladwin County and Gibson Township, Bay County.

increase the local relief along its western and southwestern flanks to as much as 35-40 ft/mi^2 in contrast to the 5-15 ft/mi^2 that is typical along its proximal slope.

The 1-4.5 mile-wide waterlain portion of the moraine in Saginaw and Tuscola counties, from Bridgeport eastward to the Vassar area, presents a similar topographic appearance. Here, too, the relatively smooth crest decreases in elevation toward the Saginaw River from 680-690 feet just west of Vassar to about 625 feet in the area north of Bridgeport. The low relief (5-10 ft/mi^2) of this part of the moraine is typical of its waterlain character.

The largest hummocky segment of the Port Huron Moraine in the study area trends northeastward across Tuscola County from Vassar to Gagetown. Like its subaerially-emplaced counterpart in northern Bay County, this part of the moraine exhibits a strong topographic expression, attaining elevations more than 100 feet above the adjacent plains in distances of one or two miles. Although relatively narrow, only 1-3 miles wide in most places, it becomes more extensive in Elkland Township (T. 14 N., R. 11 E.) where it reaches a width of 6 miles. Throughout its length, this portion of the moraine is relatively hummocky, with local relief averaging approximately 40-60 ft/mi^2. Its crest is much more broken compared to the waterlain parts and, in general, rises in elevation from about 710 feet near Vassar to over 800 feet south of Gagetown.

Across most of the study area, the Port Huron Moraine displays an asymmetrical form, its distal slope being significantly steeper than its proximal counterpart (see Figures 9, p. 23 and 11, p. 27). The ratio of the distal slope to the proximal slope varies between 1.1:1 and 6.8:1 with an average of 2.6:1. This asymmetry may result from three factors. Primary asymmetry could occur due to the mechanics of moraine deposition directly from the ice mass. Debris in an ice lobe is usually concentrated on the surface of the marginal zone and along thrust fault planes and diminishes up-ice. Such a distribution of supra- and englacial drift, upon deglaciation, could result in an asymmetric moraine. Deposits of outwash in the form of fans or aprons along the steeper distal flank of a moraine would tend to reduce this primary asymmetry, but such deposits are notably lacking along the Port Huron Moraine (Leverett and Taylor, 1915: 298).

The impact of proglacial lakes on the Port Huron Moraine is the second factor. In many places, the distal slope of the moraine was subjected to erosion along several proglacial lake shorelines, including those of Lakes Warren, Grassmere and Elkton. In Midland and Saginaw counties, these distal slope beach zones faced into the prevailing westerly winds and must have been subjected to stronger wave action than the proximal slopes to the leeward. This situation was reversed in Tuscola County, however, and the prominent bench cut into the proximal margin of the moraine there owes its origin, at least in part, to enhanced wave action along a windward shore. According to Taylor (Leverett and Taylor, 1915: 300), the unusual strength of this feature may be the result of fluvial erosion by a meltwater stream draining to the southwest between the ice front and the moraine.

The influence of post-glacial erosion is the third factor. On both sides of the Saginaw Lowland, the Port Huron Moraine acts as a modest topographic barrier to surface drainage. The courses of both the Tittabawassee and Cass rivers are controlled to some extent by this moraine. As a result, the toe of the distal slope has been subjected to fluvial erosion which may have maintained a steeper slope through time than would otherwise have been the case. These three factors, acting in concert, may explain the asymmetrical form of the Port Huron Moraine in the study area.

Composition of the Port Huron Moraine

With the exception of the eolian and lacustrine sands scattered across its surface, the Port Huron Moraine is composed of a clay-rich drift throughout the Saginaw Lowland, as noted by Taylor (Leverett and Taylor, 1915: 297), although loam is the most frequently mapped parent material texture.

The pedologic distinction between the waterlain portions of the moraine and its more rugged counterparts is primarily a difference in slope class and soil drainage characteristics. In general, the subaerially deposited parts of the moraine are composed of well, moderately well, or somewhat poorly drained soils having slopes of up to 12 percent. The waterlain segments, on the other hand, consist of poorly and somewhat poorly drained soils, with slopes of no more than 3 percent. Tables 1 and 2 summarize the predominant soil types associated with these two moraine categories.

The distal border of the Port Huron Moraine in Midland County, as delimited in this study, is two to four miles west of its previously recognized location, an increase in area of about 34 square miles. Figure 12 depicts the soils of Larkin (T. 15 N., R. 2 E.) and Midland (T. 14 N., R. 2 E.) townships as generalized from Hutchison (1979). The genetic implications of these parent material distributions support the inclusion of this area within the moraine.

On the west side of Larkin and Midland townships, glaciofluvial sediments and more recent alluvium cover the Tittabawassee River outwash channel and have, to varying degrees, been modified by wind action. These deposits consist primarily of Belleville loamy sand, Covert sand, Kingsville loamy fine sand, Kinross mucky sand, Oakville fine sand, Pipestone sand, Sloan loam and Wixom loamy sand.

Table 1

Predominant soil types associated with the waterlain segments of the Port Huron Moraine in the Saginaw Lowland

County	Soil Mapping Unit Name	Soil Management Group*	Slope Class (%)
Bay	Londo-Poseyville complex	2.5b & 3/2b	0-3
	Tappan-Poseyville complex	2.5c-c & 3/2b	0-3
	Poseyville loamy sand	3/2b	0-3
	Tappan loam	2.5c-c	0-3
	Londo loam	2.5b	0.1
Saginaw	Capac sandy loam-Brookston loam	2.5b & 2.5c	0-3
	Capac-Brookston loams	2.5b & 2.5c	0-3
	Wixom-Thetford-Arenac loamy sands	4/2b, 4b & 5/2b	0-3
	Arenac - Kingsfield sands	5/2b & 5c	0-3
	Capac-Shebeon-Parkhill loams	2.5b, 2.5b & 2.5c	0-3
	Parkhill-Kilmanaugh loams	2.5c & 2.5c-d	0-3
	Sims clay loam-Parkhill loam	1.5c & 2.5c	0-3
Tuscola	Parkhill-Londo loams	2.5c & 2.5b	0-2

*See Appendix A.

Table 2

Predominant soil types associated with the subaerially-emplaced segments of the Port Huron Moraine in the Saginaw Lowland

County	Soil Mapping Unit Name	Soil Management Group*	Slope Class (%)
Bay	Londo-Wixom complex	2.5b & 4/2b	0-4
	Guelph-Menominee complex	2.5a & 4/2a	2-8
	Wixom loamy sand	4/2b	0-3
Tuscola	Guelph loam	2.5a	0-12
	Londo loam	2.5b	0-2
	Boyer-Manceolona loamy sands	4a & 4a	0-6
	Marlette-Menominee association	2.5a & 4/2a	0-6

*See Appendix A.

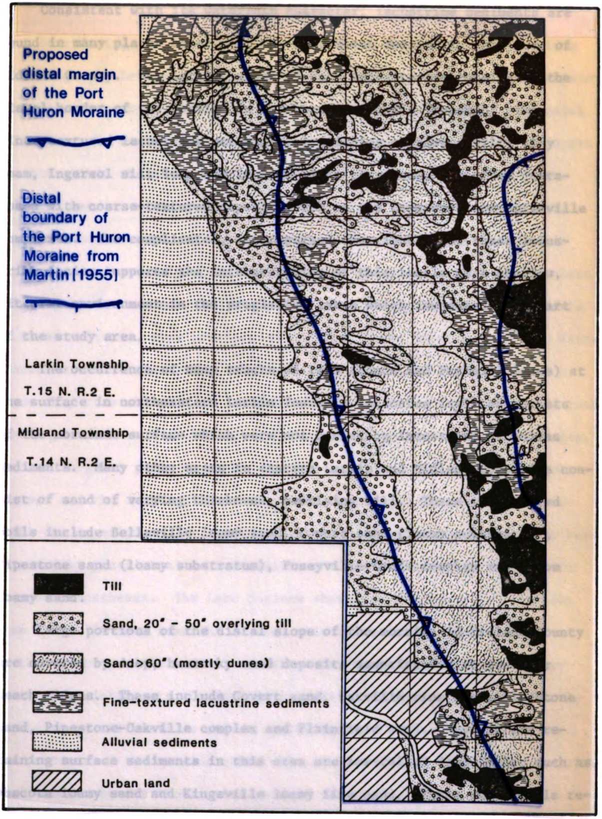


Figure 12. Parent materials of the soils in Larkin and Midland townships, eastern Midland County.

Consistent with its waterlain character, lacustrine sediments are found in many places on or near the Port Huron Moraine in this part of Midland County. The largest areas of such deposits are outside of the distal border of the moraine in northwestern Larkin Township. The finer-textured lacustrine materials, consisting of Bowers silty clay loam, Ingersol silt loam and Lenawee silty clay loam, are often juxtaposed with coarse-textured deposits such as the Lenawee-Wixom-Belleville complexes. The complicated, interspersed distribution of these lacustrine facies supports the interpretation of this locale as a shallow, littoral environment in the proglacial lakes which inundated this part of the study area.

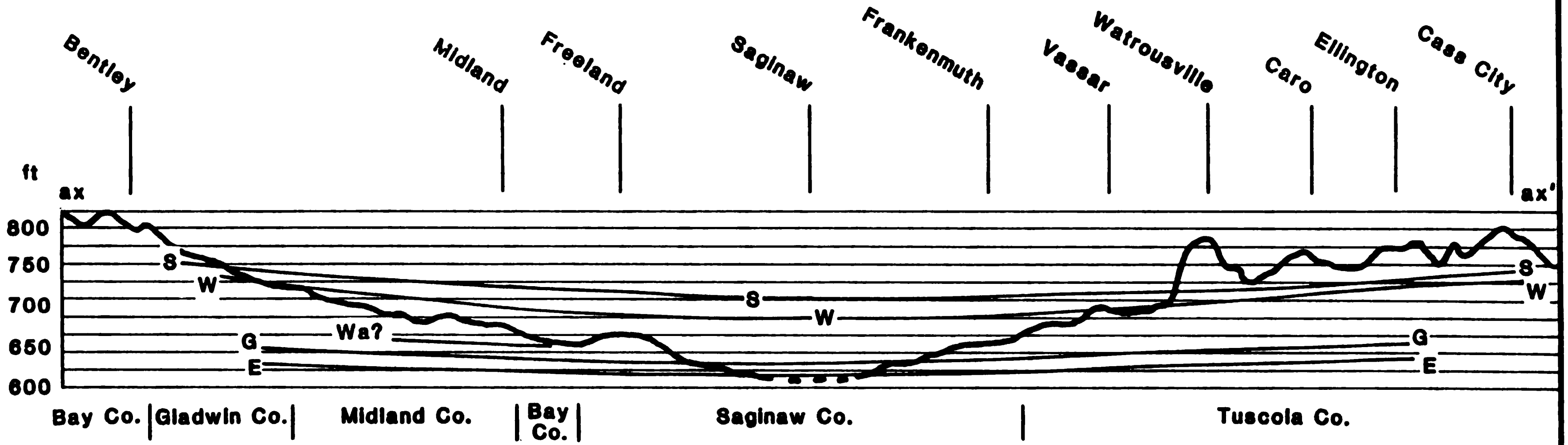
The occurrence of many tracts of till (Londo and Parkhill loams) at the surface in northeastern Larkin Township indicates isolated pockets of the morainic surface which were not buried by lacustrine or eolian sediments. Many other areas in eastern Larkin and Midland townships consist of sand of varying thickness, overlying till. These two-storied soils include Belleville loamy sand, Covert sand (loamy substratum), Pipestone sand (loamy substratum), Poseyville-Londo complex and Wixom loamy sand.

Large portions of the distal slope of the moraine in Midland County are covered by deep, hummocky sand deposits associated with dunes or beach ridges. These include Covert sand, Oakville fine sand, Pipestone sand, Pipestone-Oakville complex and Plainfield sand. Most of the remaining surface sediments in this area are low-relief deep sands, such as Abscota loamy sand and Kingsville loamy fine sand. These sandy soils represent deltaic materials which were deposited in the littoral zones of several progressively lower proglacial lakes, particularly those of the Warren and Grassmere phases.

Waterlain Moraines

Even during the reconnaissance mapping of the surficial formations of Michigan by Leverett and Taylor (1915), it was recognized that certain moraines, in part of in total, had been deposited in standing proglacial meltwater. As mentioned previously, extensive segments of the Port Huron Moraine within the study area were emplaced in this manner. Among the criteria used to distinguish waterlain moraines from their subaerially deposited counterparts are their comparatively more subtle topographic expression and muted local relief, although the mechanism(s) of waterlain till deposition are not well understood (Dreimanis, 1979). On the basis of these criteria, most portions of the Port Huron Moraine above the Warren shorezone can be classified as a typical, subaerially-emplaced moraine since they rise abruptly to as much as 100 feet or more above the adjacent landscape and have high-relief surfaces averaging 40-60 ft/mi^2. However, the ice marginal position marked by this moraine-dammed proglacial Lake Saginaw and the level of this water body determined how much of the moraine was waterlain. The shorezone of this meltwater impoundment has been deformed by postglacial rebound and in the modern landscape it rises to the north-northeast. The Lake Saginaw shoreline increases in elevation from about 715 feet near the central axis of the study area to 750 feet in the vicinity of Cass City. As shown in Figure 13, the Lake Saginaw water plane intersects the Port Huron Moraine at about 725 feet a little southwest of Watrousville and at approximately 750 feet near Cass City. The portions of the moraine above this place were deposited in a subaerial environment whereas those below it were waterlain.

A conjugate situation can be observed in northern Bay County and southwestern Gladwin County where the rugged portions of the Port Huron Moraine are also restricted to elevations above 750 feet, flanked on the



		horizontal zone elevation (ft)	study area elevation (ft)	
			minimum	maximum
S	Lake Saginaw	695	715	750
W	Lake Warren I	680	685	730
Wa?	Lake Wayne ?	660	655	660
G	Lake Grassmere	640	640	655
E	Lake Elkton	620	620	640

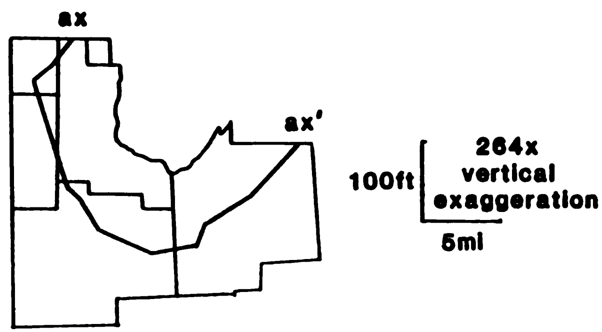


Figure 13. An expanded topographic profile along the crest of the Port Huron Moraine and the deformed water planes of selected proglacial lakes in the Saginaw Lowland.

south by a waterlain apron between 725 and 750 feet which was deposited in a subaquatic environment.

Proglacial Lake Sequence and Chronology

During the Late Wisconsinan, the Saginaw Lowland was the site of several proglacial lakes. These meltwater impoundments affected the type and distribution of several landforms, particularly waterlain moraines. They influenced the texture of soil parent material and left as their geomorphic legacy a series of erosional and depositional shorezone features. Although numerous lakes of similar origin may have existed in the Saginaw Lowland at various times throughout the Pleistocene, direct surface evidence can be found for only those which came into existence during the Late Wisconsinan.

The Saginaw Lowland, and probably all of the Lower Peninsula of Michigan, was ice-free about 13,300 yrs B.P. during the Mackinaw Interstadial (Farrand, Zehner and Benninghoff, 1969; Dreimanis, 1977). Any lake which may have occupied the Huron Basin at that time was below the present lake level of 580 feet (Hough, 1963; Dreimanis and Goldthwait, 1973).

During the subsequent Port Huron Stadial, the ice readvanced and built the Port Huron Moraine. This major ice advance blocked lower drainage outlets to the east and resulted in an independent, high-level, proglacial lake in the Saginaw Lowland which drained westward through the Maple-Grand outlet. Lake Saginaw, shown in Figure 14, received meltwater from both Lake Whittlesey, impounded in the Huron basin to the east, via the Tyre-Ubly channels, as well as from numerous outwash streams. In addition, some meltwater from the interlobate area of Oscoda and Alcona counties to the north was channeled southward along the ice margin and entered Lake Saginaw near West Branch in southwestern Ogemaw County.

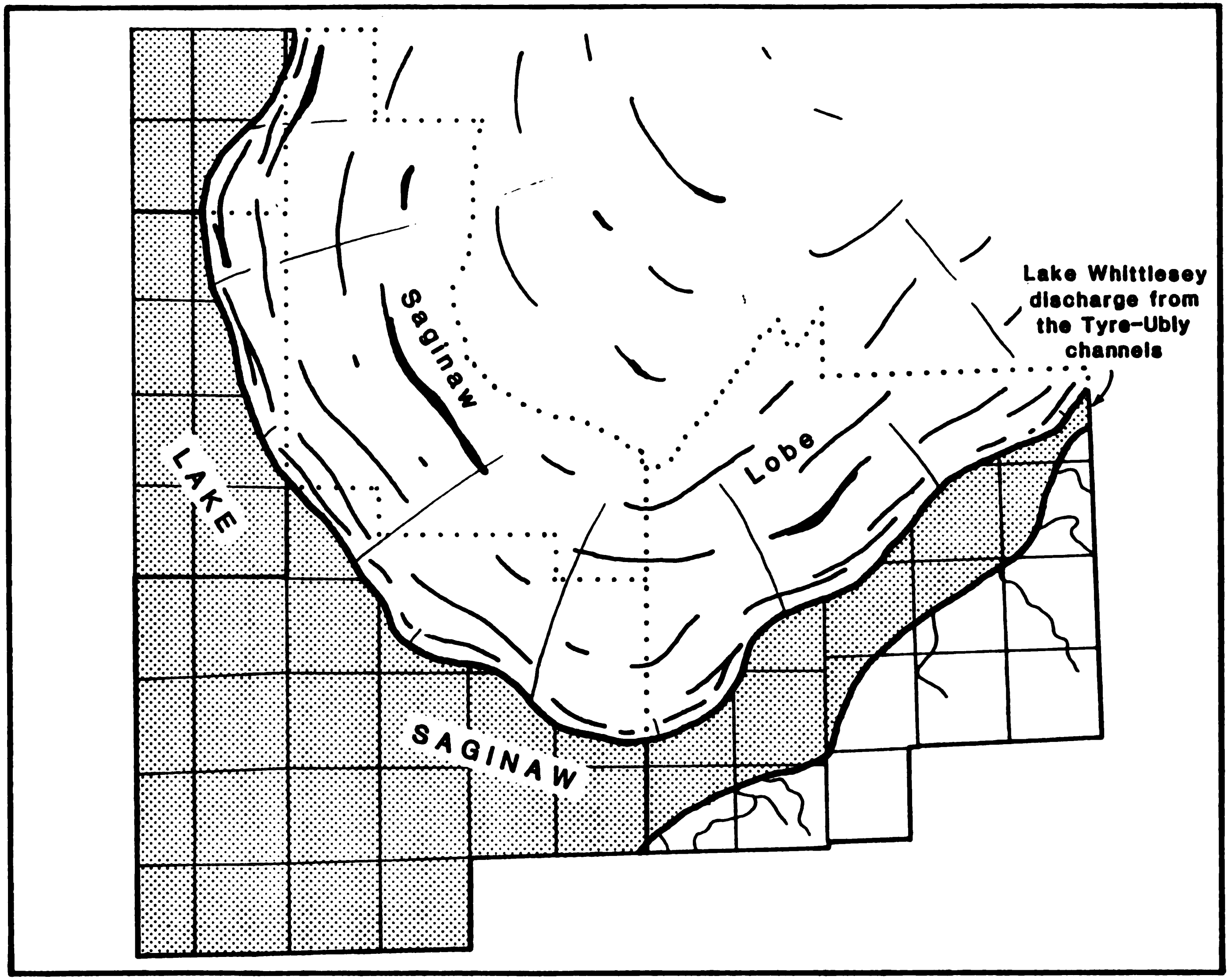


Figure 14. Lake Saginaw during the maximum Port Huron Stadial.

As shown in Table 3, five radiocarbon dates have been determined for wood samples associated with Lake Whittlesey sediments or those that are transitional between Lake Arkona and Lake Whittlesey. The average of these dates is 12,976 ± 524 yrs B.P. suggesting an age of about 13,000 yrs B.P. for the correlative Lake Saginaw and Port Huron Moraine.

As discussed earlier, Lake Saginaw had an elevation of about 750 feet in the vicinity of Cass City near the mouth of the Lake Whittlesey discharge. The entire study area is north of the Saginaw/Whittlesey zero isobase so the 695 foot elevation of the lake in the horizontal zone does not apply (Leverett and Taylor, 1915). Instead, evidence of the Lake Saginaw shoreline throughout the Saginaw Lowland occurs at or above 715 feet.

Nearly 300 years later, the tip of Michigan's "thumb" was uncovered and the proglacial lake in the Saginaw Lowland once again became an embayed extension of the Huron basin. At this time, the water plane fell to a new level of 680 feet (in the zone of horizontality) and Lake Warren, which also discharged to the west via the Maple-Grand system, came into existence (Figure 15). Within the study area, most of which is north of the Warren hinge line (Leverett and Taylor, 1915), the Warren shoreline has been deformed by postglacial rebound to its present elevational range of 700 to 725 feet. The Warren I stage has been assigned an age of 12,730 ± 230 yrs B.P. (I-3665) on the basis of wood samples from a site on the edge of the Erie Lowland in western New York (Calkin and McAndrews, 1969; Buckley, 1976). This sample (I-3665) came from a peat zone which was deposited either during a late stage of Lake Whittlesey or during the highest Lake Warren stage (Warren I) which followed. According to Calkin (1970), the elevation of the dated sample, only five feet below the projected Warren I water plane, and its association with the remains of

Table 3

Radiocarbon ages of materials associated with Lake Whittlesey or the Lake Arkona-Lake Whittlesey transition

C^{14} Age (yrs B.P.)	Sample No.	Remarks	Reference
12,660 ± 440	S-31	Sample from a waterworn Larix log 2.5" x 2.5' from 32'-42' beneath the surface of an Arkona-Whittlesey bar at Ridgetown, Ontario. Elevation = 703'-713' A.T. Highest Warren beach (705') is 1 mile SE.	Dreimanis, 1966
13,600 ± 500	W-33	Wood from a stratigraphic position between deposits of Lake Arkona and Lake Whittlesey near Cleveland, Ohio.	Suess, 1954
12,920 ± 400	W-430	Wood from peaty zone below Lake Whittlesey beach gravels at Ohio Turnpike-Ohio Rte. 4 intersection in Erie County. Underlying the peat is sandy alluvium and lake clay over calcareous till. Near Parkerstown, Ohio.	Rubin & Alexander, 1958
12,800 ± 250	Y-240	Spruce wood fragments imbedded in beach sediments of glacial Lake Whittlesey from a well 4.5 miles SE of Bellevue, Ohio.	Barendsen et al., 1957
12,900 ± 200	I-3175	Wood in Whittlesey beach near Elyria, Ohio.	Calkin, 1970

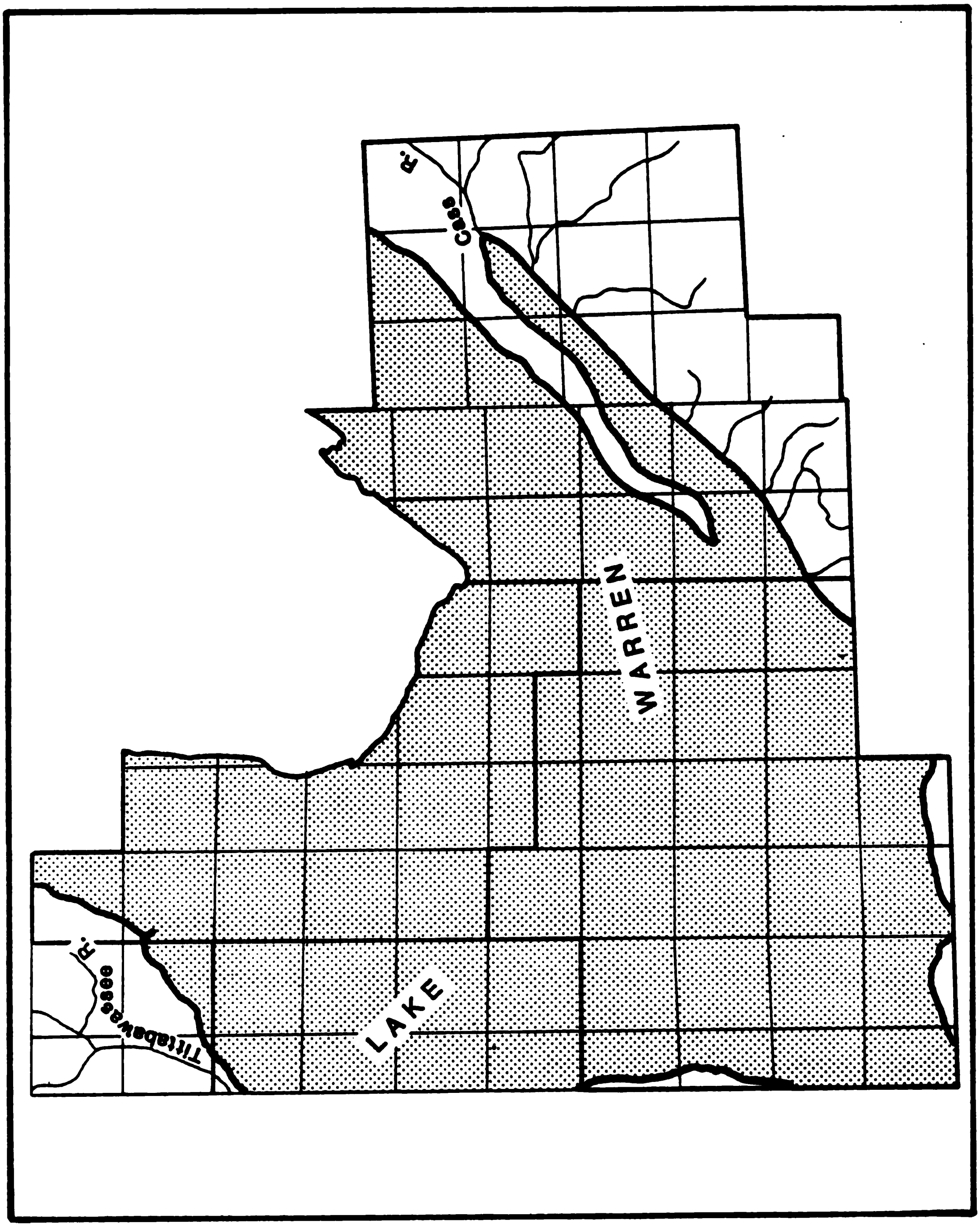


Figure 15. Lake Warren I during the waning Port Huron Stadial.

shallow-water flora favor its correlation with the Warren I stage.

According to Hough (1963), after Lake Warren had been lowered to 670 feet (Warren II), it fell temporarily to the level of Lake Wayne (660 feet) and then rose to the Warren III elevation of 665 feet. Little evidence can be found in the study area for any post-Warren I levels above the Grassmere shoreline. Nevertheless, there are some landscape features which suggest a shorezone on top of the waterlain Port Huron Moraine in western Bay and eastern Midland counties. These consist of relatively narrow, curvilinear zones of sandy material which frequently contain low ridge forms. These minor topographic features are usually faint but they occur in many places and, in association with the sandy soils, seem to define a former shorezone at 655-660 feet which may be associated with Lake Wayne or some other minor halt in the progressive lowering of Lake Warren.

As the Twocreekan Interstadial continued, the levels of the glacial Great Lakes in the Huron and Erie basins fell to even lower elevations as new outlets became operative. Progressive ice margin retreat in the vicinity of Syracuse, New York allowed meltwater to flow eastward via the Mohawk Valley and, as a result, Lake Grassmere came into existence. This proglacial impoindment (Figure 16) had an elevation of 640 feet in the zone of horizontality which includes most of the study area. North of its zero isobase, in northern Bay and Tuscola counties, the Grassmere shoreline rises to about 650-655 feet.

Lake Elkton (Lundy) was the next proglacial lake in this short-lived series and its horizontal shoreline segments have an elevation of aboug 620 feet (Figure 17). Elkton shorelines deformed by rebound in northern Bay County are found at 630 feet while those in northeastern Tuscola County reach the 640 foot level.

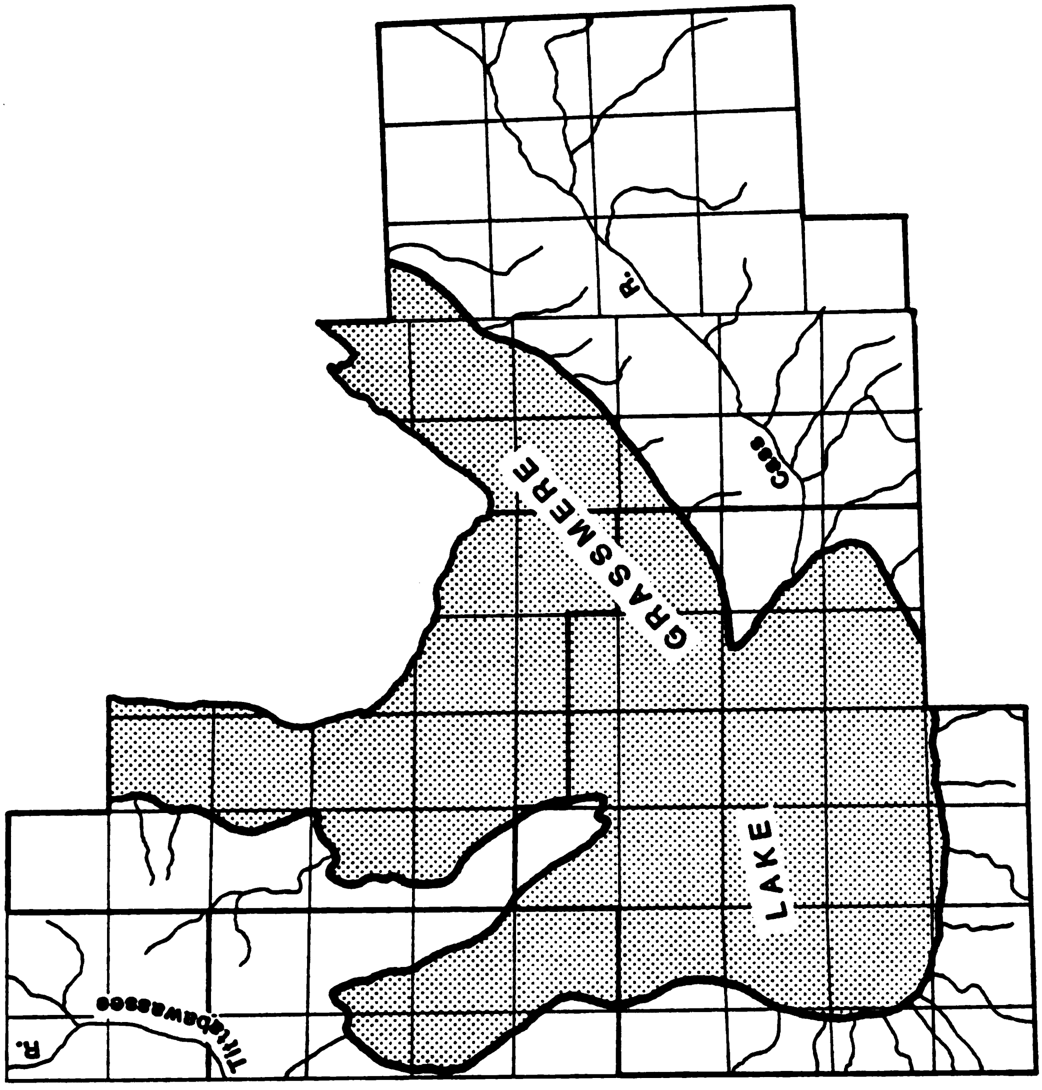


Figure 16. Lake Grassmere during the waning Port Huron Stadial.

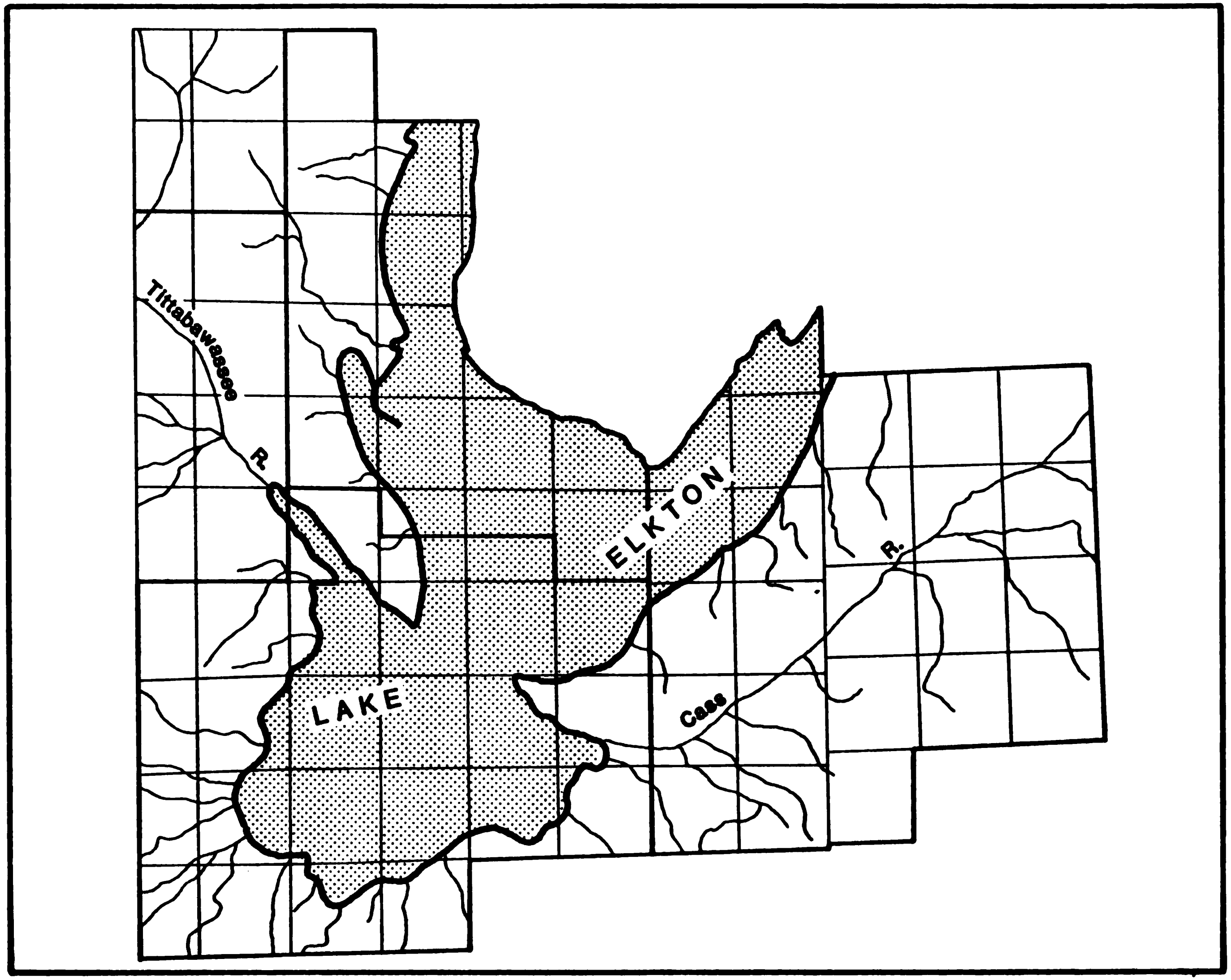


Figure 17. Lake Elkton during the waning Port Huron Stadial.

Following the Elkton stage, continued downcutting of the Chicago outlet eventually formed Early Lake Algonquin at an elevation of about 605 feet, but no shorelines or other features associated with this proglacial lake are knwon (Karrow et al, 1975). The oldest radiocarbon dates on plant detritus and wood correlated with Early Lake Erie and Lake Iroquois, contemporaries of Early Lake Algonquin, average 12,373 ± 466 yrs B.P. and are summarized in Table 4. Thus, Early Lake Algonquin probably came into existence about 12,400 years ago. Continuing ice margin retreat into Ontario opened the Kirkfield-Trend Valley outlet to the east and,

Table 4

Radiocarbon ages of materials associated with Early Lake Erie and Lake Iroquois

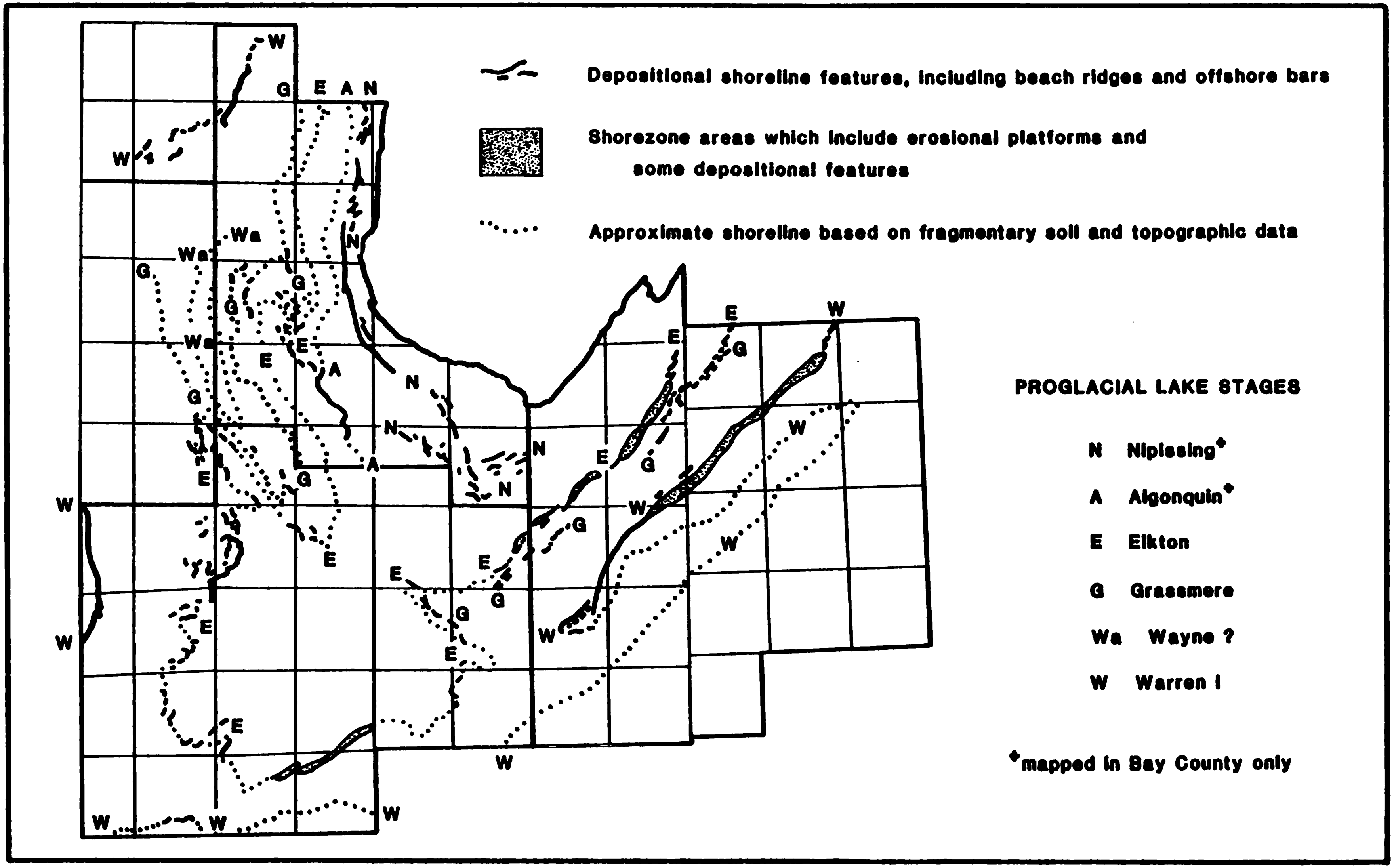
C^{14} Age (yrs B.P.)	Sample No.	Remarks	Reference
12,650 ± 170	I-4040	Basal plant detritus associated with Early Lake Erie from the Pelee Basin of western Lake Erie.	Lewis, 1969
12,660 ± 400	W-861	Sample from *Picea mariana* log in laminated silt and clay deposits of Lake Iroquois at 340' near Lewiston, New York.	Rubin & Alexander,
12,080 ± 300	W-883	Sample of another *Picea mariana* log collected from the same place at the same time as W-861.	Rubin & Berthold, 1961 Muller, 1965
12,100 ± 400	I-838	Spruce wood in Lake Iroquois sediment 4.5 miles N of Lockport, New York.	Buckley et al., 1968

beginning about 12,000 yrs B.P., the lake level in the Huron basin was once again below its present level of 580 feet (Karrow et al., 1975). It is unclear whether crustal rebound or a minor ice advance caused the abandonment of the Kirkfield outlet, but whatever the cause, Karrow et al. (1975) concluded that as a result of its closure, Main Lake Algonquin formed at an elevation of 605 feet approximately 11,200 yrs B.P.

Discontinuous segments of the relict shorelines of several Late Wisconsinan proglacial lakes can be traced across the study area as shown in Figure 18. Shorelines at or above the Elkton level, excluding the pre-Warren stages, were delineated because of their spatial relationship to either the Port Huron Moraine or the patterned ground, or both (Lusch, 1977). The proglacial lakeshore features below the Elkton beach were not investigated, except for those portions of the Algonquin and Nipissing shorelines in Bay County which were relevant in the search for the Bay City Moraine.

The depositional landforms depicted in Figure 18 consist mainly of low, sandy ridges representing either beach ridges or offshore bars. The stippled shorezone areas define landscapes which are dominated by erosional features, such as wave-cut nicks and benches, but also include some depositional forms. The shoreline segments shown by the dotted lines are probably not as accurately located as the other types, since they are based on incomplete or less convincing evidence. Nevertheless, their trends are clearly indicated and the zone of uncertainty containing their true locations is limited to perhaps a few thousand feet on either side of the plotted lines.

The morphologically most distinct shoreline erosion was developed along the southeastern margins of the Warren and Elkton basins, consistent with the presumption of prevailing westerly winds. In southwestern Bay


Depositional shoreline features, including beach ridges and offshore bars
Shorezone areas which include erosional platforms and some depositional features
Approximate shoreline based on fragmentary soil and topographic data
PROGLACIAL LAKE STAGES
N Nipissing+
A Algonquin+
E Elkton
G Grassmere
Wa Wayne ?
W Warren I
+mapped in Bay County only

County, several spits, attributed to both the Grassmere and Elkton lake levels, were identified and mapped. Other depositional shoreline features of Lake Elkton in western Saginaw County have been significantly modified by wind action and, as a result, the location of this segment of its shore may be shown too far to the east. The generally weak character of most of these glaciolacustrine shorelines is probably a function of the short time interval during which any particular lake level was maintained.

As will be discussed later, the lower elevational limit of the patterned ground is coincident with the shoreline of proglacial Lake Elkton in the central and eastern part of the study area where numerous depositional and erosional landforms mark this former coastline. This morphologic relationship continues northeastward across the hinge line into the uplifted zone where Elkton beachridges rise from their horizontal elevation of 620 feet to 640 feet. This spatial association was utilized to map the Elkton shorezone in Bay and north-central Saginaw Counties where other geomorphic evidence of the Elkton beach is lacking.

In comparison with previous interpretations, as summarized by Martin (1955), the present delineation of the proglacial lake shorelines in the Saginaw Lowland is of considerably greater accuracy in Bay and north-central Saginaw Counties. Additionally, the location of the Grassmere beach within the study area was previously undefined. Although these glaciolacustrine features are not the principal focus of this research, their locations throughout the Saginaw Lowland had to be determined in order to establish the relative time-stratigraphic position of the patterned ground.

Eolian Landforms

In light of the Late Wisconsinan history of the area, it is not surprising that sand dunes are abundant in the Saginaw Lowland. Each of the proglacial lakes which inundated this area had the potential of depositing sandy material along its shoreline; additional sediments which were susceptible to subsequent deflation were provided by the numerous prograding deltas that were extending into these meltwater impoundments. Perhaps even more important than these littoral and deltaic sediments, however, were the glaciofluvial deposits. Particularly in the western part of the study area, the dense network of low-gradient rivers and creeks undoubtedly provided expansive areas of sandy material after each flooding.

The largest concentrations of sand dunes in the Saginaw Lowland are located in eastern Midland, western Bay and southwestern Saginaw counties. Additionally, many tracts of land south of the Cass River in Tuscola County are covered by dune forms. Dune formation was favored in these areas because of the abundant availability of sandy materials derived primarily from the many sediment-laden streams.

Thus, the Tittabawassee, Cedar and Tobacco rivers in southwestern Gladwin and north-central Midland counties, as well as the upper Cass River and the headward reaches of many of its modern tributaries in Tuscola County, all deposited large quantities of sediment, not only on their floodplains, but also into Lake Warren (see Figure 15, p. 41). With the lowering of the water plane to the Grassmere and then Elkton levels (see Figures 16 and 17, pp. 43 and 44), the Cass River became fully established in Tuscola County and emptied into the proglacial impoundments in southeastern Saginaw County. At the same time, the headward reaches of the Shiawassee River and many of its tributaries provided copious amounts of alluvium to the proglacial lakes in southwestern Saginaw County. In eastern Midland County, the Chippewa and Pine rivers contributed their sediment loads to that of the Tittabawassee River.

All across the Saginaw Lowland, the parabolic dune form predominates (see Figure 10 and Plate II, pp. 25 and 26), although in many places, particularly in the western part of the study area, the dune ridges have been drawn out downwind to form hairpin dunes. Virtually everywhere in the Saginaw Lowland the axes of these inland dunes trend west-northwest to east-southeast. In this part of Michigan, eolian landforms developed as the landscape emerged from beneath the progressively lowering proglacial lakes of the Late Wisconsinan. They document a late-glacial paleoenvironment in which eolian processes were dominant and indicate 1) that vegetation was probably scarce in the immediate periglacial zone of the Saginaw Lowland at this time and 2) that the prevailing wind direction during the Late Wisconsinan was essentially the same as today, namely westerly.

CHAPTER III

CHARACTERISTICS OF THE PATTERNED GROUND IN THE SAGINAW LOWLAND

Distribution and Extent of the Patterned Ground

In the only other study of the patterned ground in the Saginaw Lowland, Tillema (1972) analyzed approximately 135 mi^2 of terrain in southwestern Bay and north-central Saginaw counties. Although it was stated that patterned ground could be observed in Midland County and as far north as northern Bay County, no attempt was made to map its extent beyond the boundaries of the aforementioned study area.

The present study expanded the search area considerably by including all of Bay, Saginaw and Tuscola counties, as well as the eastern two-thirds of Midland County, the southeastern quarter of Gladwin County and the southwestern margin of Huron County. Figure 19 depicts in a general way the distribution and extent of patterned ground in the study area, which encompasses nearly 2,500 mi^2. The boundary lines shown on this map represent the outermost limits beyond which no patterns could be observed on aerial photographs; they enclosed approximately 360 mi^2 of patterned terrain within which areas of especially prominent patterned ground are shown. Most of these patterns occur in Bay, Saginaw and Tuscola counties. Since conspicuous patterns were not observed on airphotos of southwestern Huron County, the boundary lines were halted at the northern border of Tuscola County although the zone of pattern formation probably continues northeastward for one or two miles.[1]

[1] Although Huron County appears to be devoid of patterned ground, another area of distinct ground patterns is obvious on aerial photographs of eastern Sanilac County.

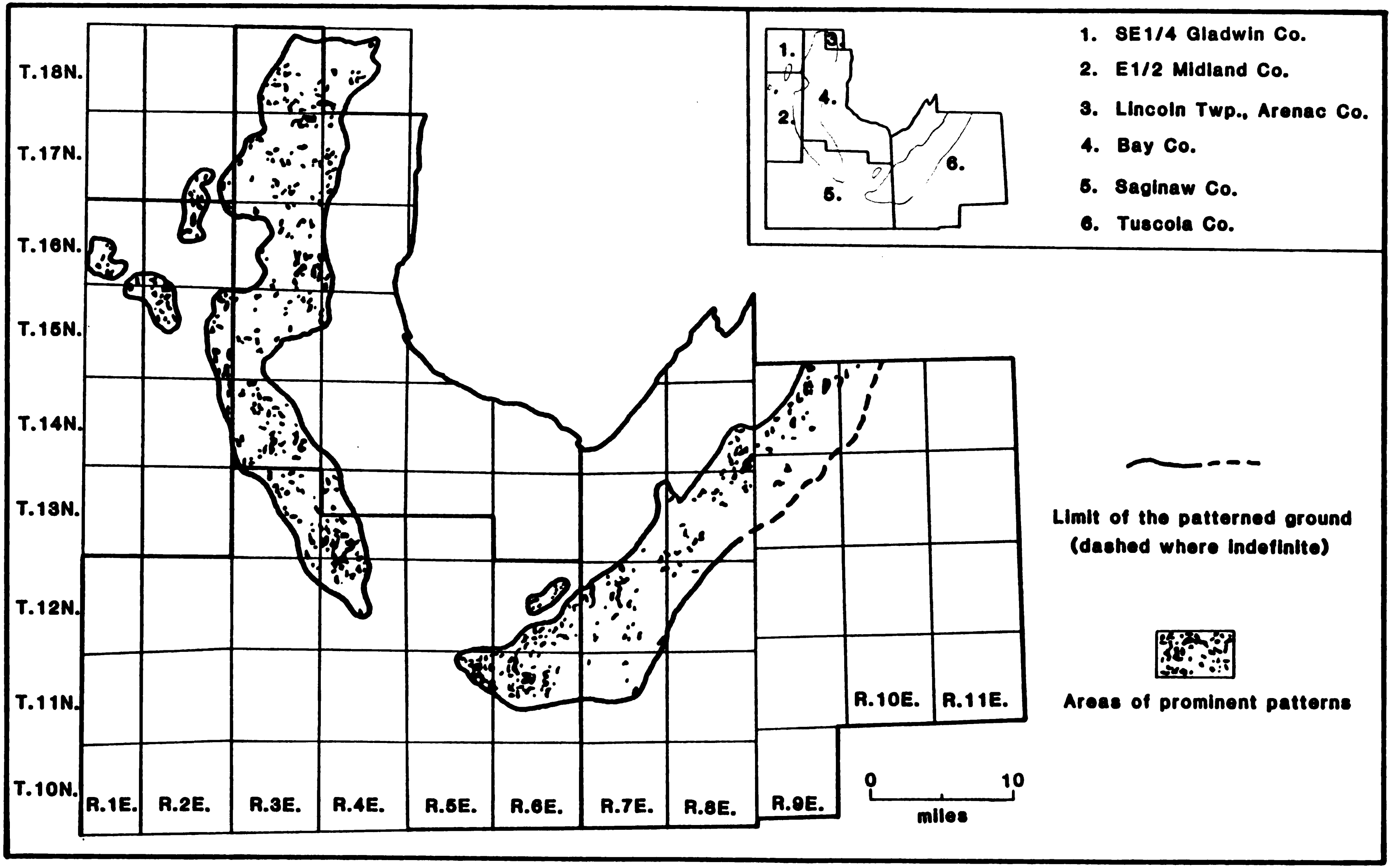


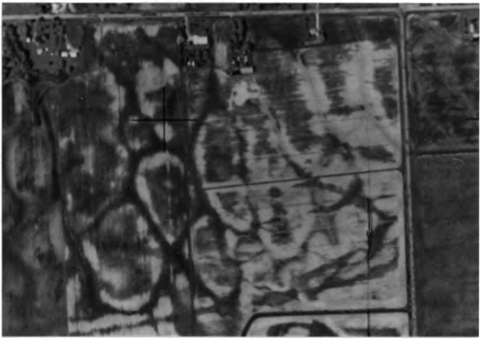
Figure 19. Distribution and extent of patterned ground in the Saginaw Lowland.

Variations in soil moisture accentuate the mesh of many of the patterns in the study area and are particularly obvious on CIR photos taken in the spring. Dry mineral soils exhibit increased infrared reflectivity and are rendered in hues of white to light cyan on CIR film. Moist soils, on the other hand, absorb infrared radiation and appear as medium to dark cyan hues (Stoner et al., 1980). Typically, the mesh of the Saginaw Lowland patterns is of a darker cyan color than the surrounding ground on CIR imagery, indicating its higher moisture content (Plate III; Figure 20).

Classification of the Patterns

Many schemes to classify patterned ground have been developed, but the one most widely accepted employs a purely descriptive terminology, based on geometric form and the presence or absence of sorting (Washburn, 1956). This system recognizes circles, nets, polygons, steps and stripes as the principal geometric forms, each of which can be either sorted or nonsorted. Nicholson (1969) has proposed an adaptation of this classification based on three criteria: pattern form, pattern grouping and the manner in which the pattern is marked. Four configurations (equiform, elongate, stripe or step) and three classes of grouping (isolate, grouped or contiguous) are recognized. Additionally, variations in either relief, particle size, or vegetation are recorded as the mode of pattern marking.

The patterned ground in the Saginaw Lowland falls into the class of nonsorted nets in Washburn's (1956) scheme because its geometric unit is primarily ovoid and rather than surficial sorting, microrelief is the major variable marking the patterns. In Nicholson's (1969) terminology, these features could be classified as "grouped, relief elongates."



(NASA-JSC 309-22-143; May 13, 1975)

Plate III. Color-infrared airphoto showing the network of nonsorted patterned ground at the Lawndale site.

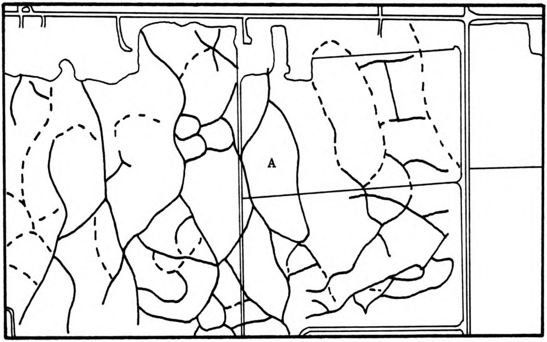


Figure 20. Mesh of the nonsorted nets at the Lawndale site as interpreted from the airphoto in Plate III.

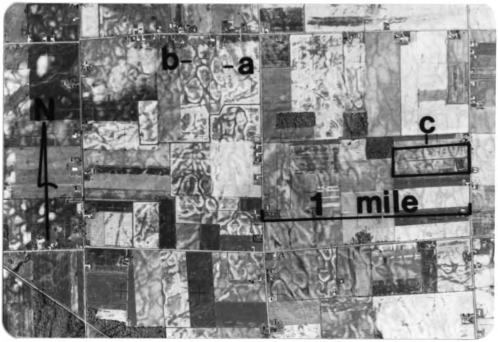
Surface Morphometry of the Saginaw Nonsorted Nets

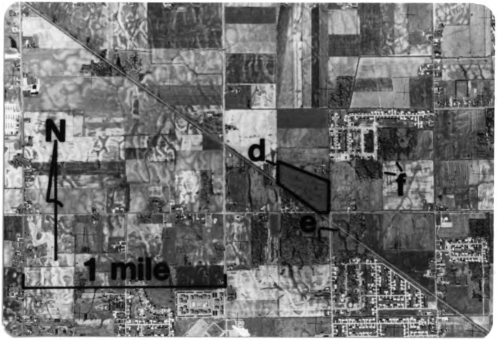
The mean dimensions of a net cell in the Saginaw Lowland are 380 x 223 feet (rms 127 x 69 ft) and ranged from very large, elongated features measuring 1,289 x 480 feet to smaller, circular forms 79 feet in diameter. Most of the mesh cells in the study area are somewhat elongated, as indicated by the 1.7:1 average a/c ratio (range = 1:1 to 3:1). The ratio of major to minor axis length (a/c) is a measure of the elongation of the form. A ratio of 1 indicates a more or less circular feature, while larger ratios are associated with oval-shaped patterns.

Plate IV illustrates some of the variations in the form, size and marking of the Saginaw nets. The patterns range from large, elongated features (a) to small, circular ones (b). Although frequently marked by soil moisture differences (as at a and b), the pattern mesh can also be outlined by differential crop vigor (c and d), as well as changes in the natural vegetative cover (e and f). As mentioned earlier, due to temporal variations in agricultural activities and soil moisture conditions, segments of the reticulate pattern mesh may not be obvious on a single date of aerial photographs. As a result, multi-temporal photo-interpretation is the only practical way to assess the true extent of these features. Figure 21 presents the results of an analysis of four different dates of black-and-white airphotos spanning 18 years for the vicinity of the Bridgeport wedge site in east-central Saginaw County.

Edaphic Characteristics of the Nonsorted Nets

There are nearly 100 different soil series recognized within the Saginaw Lowland. They were formed in diverse parent materials ranging from clay to sand, as well as in organic deposits. The natural drainage conditions of these soils vary from well-drained to very poorly drained.





(NASA-JSC 309-22-143; May 13, 1975; Original in color)

Plate IV. Variations in form, size and marking of nonsorted nets in the Saginaw Lowland.

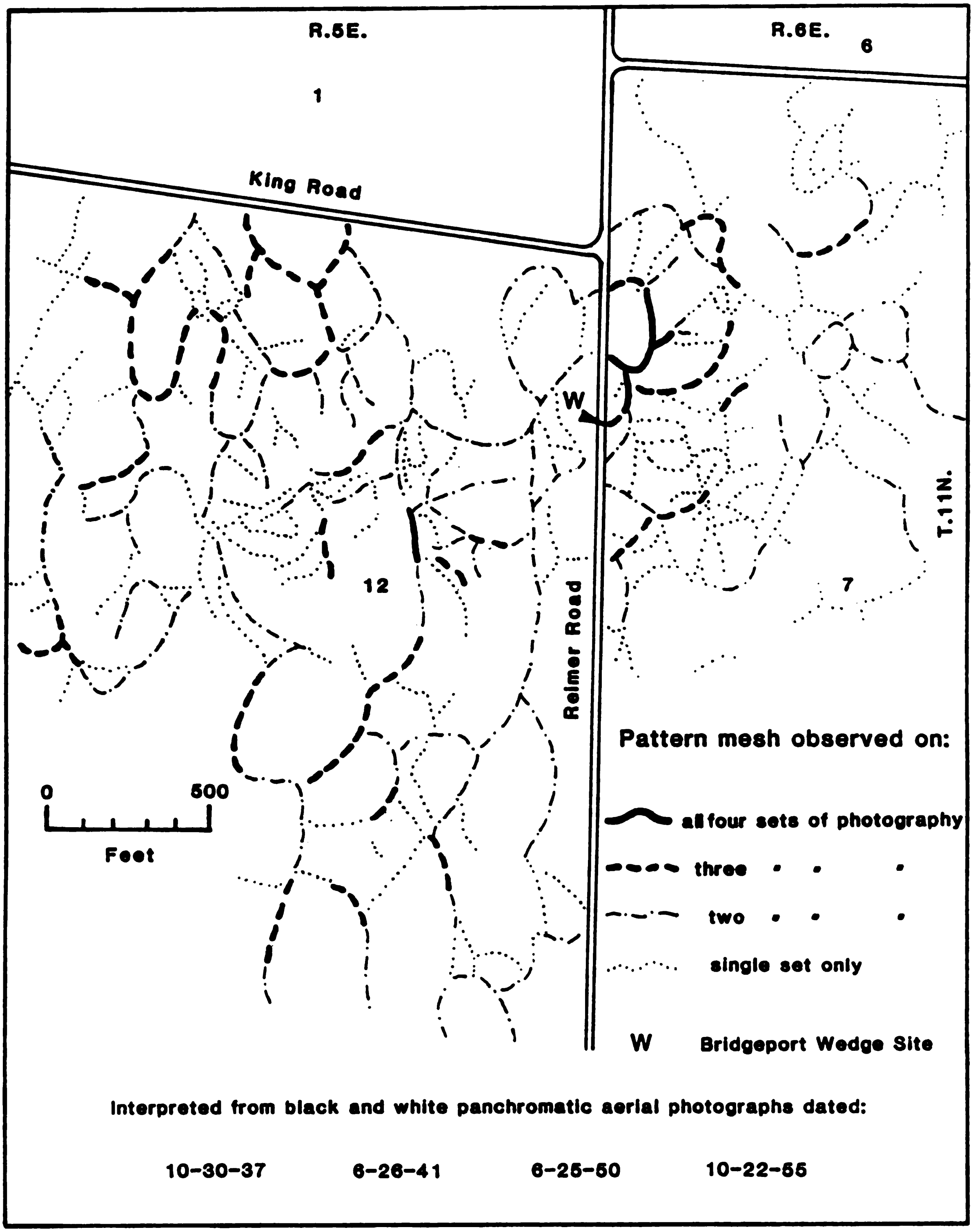


Figure 21. Delineation of nonsorted nets in the vicinity of the Bridgeport wedge.

Soil series differ from one another in the thickness and arrangement of their horizons, as well as in other physical, chemical and biological properties. For the purposes of geomorphic mapping, however, the two most important soil attributes are dominant profile texture, indicative of the depositional environment (e.g. outwash sand and gravel compared to clay loam glacial till), and the natural drainage which is suggestive of the topographic setting (e.g. well to somewhat poorly drained morainic soils compared to somewhat poorly to poorly drained drift of a lacustrine plain).

Soil management groups, the system of categorizing soil texture and drainage used in this study, designate these edaphic parameters by a set of numbers and letters.[2] The generalized soil management groups within the study area are shown in Figure 22; it reveals that most of the patterned terrain is underlain by somewhat poorly drained loam and silt loam drift or two-storied soils in which a fine-textured substrate is overlain by coarser materials.

A more detailed analysis of the soil types associated with the prominent patterns shown in Figure 19 was made by plotting their locations on the available soil maps.[3] As shown in Table 5, the majority of these patterns groups occur on somewhat poorly drained loam and silt loam soils. A lesser, but still significant, concentration is found on two-storied soils in which sandy loam or sand to loamy sand overlies loam to clay loam. An example of the spatial association between the nonsorted nets and these particular soil texture/drainage classes is shown in Figure 23.

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[2]Summarized in Appendix A.

[3]Of the soil surveys available for the study area, only Bay County (Weesies, 1980) and Midland County (Hutchinson, 1979) were recently mapped. The reports for Saginaw County (Mahjoory and Whiteside, 1976) and Tuscola County (Mokma and Whiteside, 1974) are revisions of older data (1933 and 1926, respectively) wherein various mapping units were renamed.

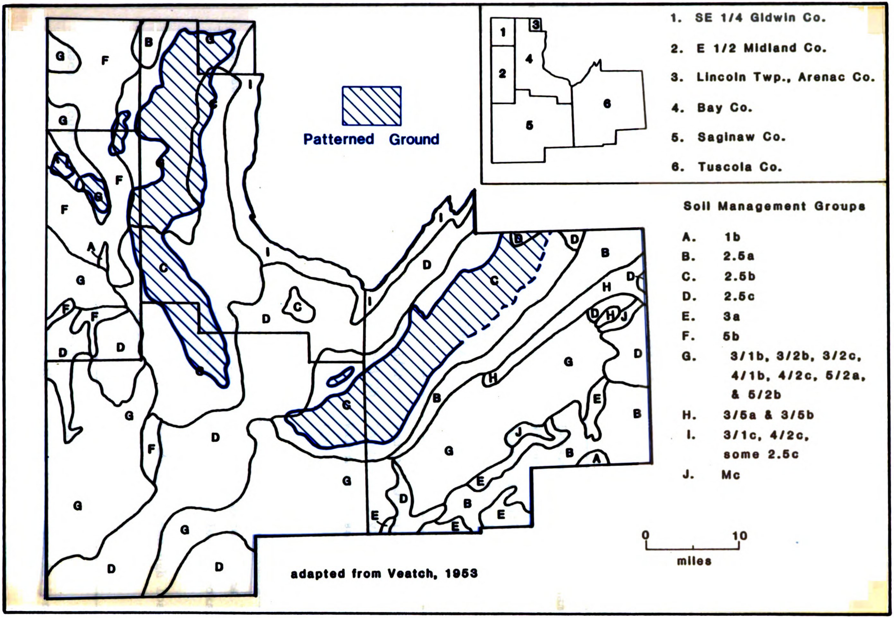
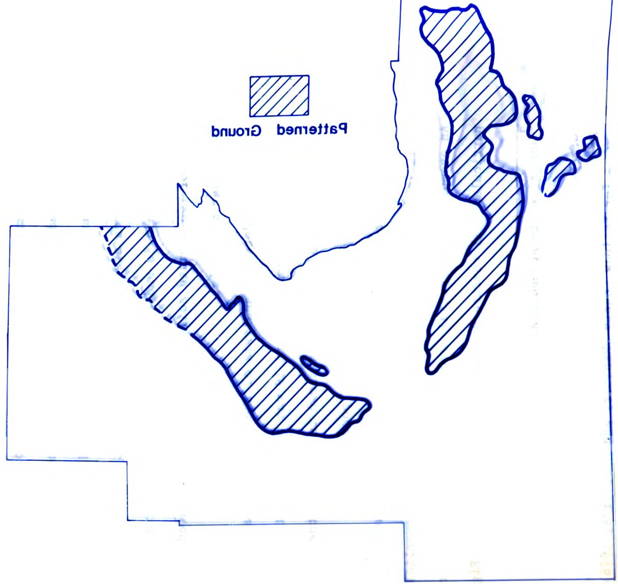


Figure 22. Relationship between soil management groups and the distribution of the Saginaw nonsorted nets.


Patterned Ground

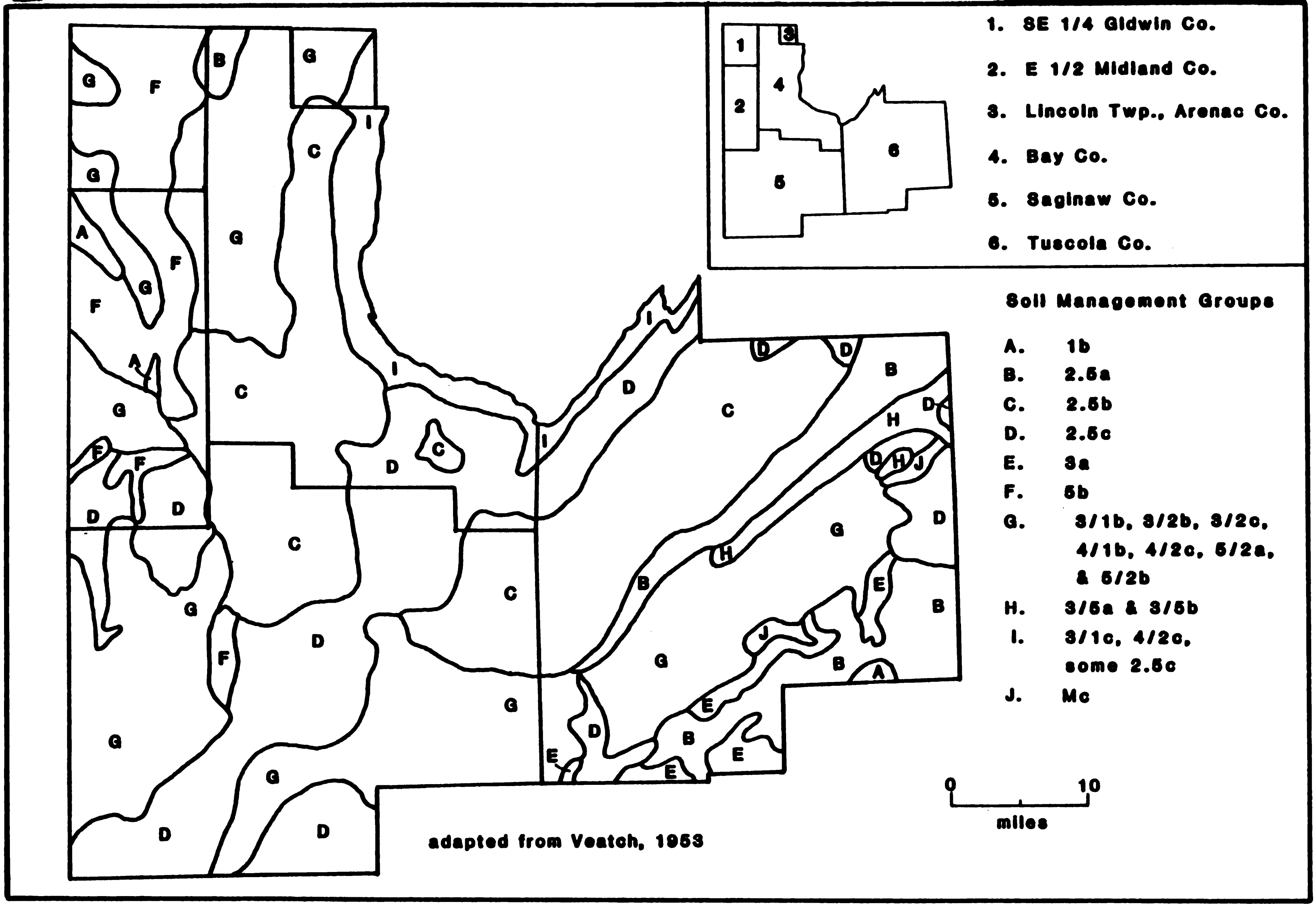


Figure 22. Relationship between soil management groups and the distribution of the Saginaw nonsorted nets.

Table 5

Frequency of occurrence of nonsorted nets by soil management groups (SMG) in the Saginaw Lowland

Area	% Frequency	SMG	Soil Series
Study Area	38	2.5b-2.5c	
	12	2.5b-3/2b	
	8	2.5c	
	7	2.5b	
	7	4/2b	
	5	2.5b-4/2b	
	23	others	
Midland County	29	1.5c	Lenawee silty clay loam
	21	4/2b	Wixom loamy sand
	17	2.5b-s	Ingersoll silt loam
	12	1.5b	Bowers silt loam
	21	others	
Bay County	39	2.5b-3/2b	Londo-Poseyville
	16	2.5c-c-3/2b	Tappan-Poseyville
	16	4/2b	Wixom loamy sand
	10	2.5b	Londo loam
	19	others	
Saginaw County	38	2.5b-2.5c	Capac-Brookston loams
	19	2.5b-2.5c	Capac sandy loam-Brookston loam
	14	2.5c-2.5c-c	Parkhill-Kilmanaugh loams
	29	others	
Tuscola County	54	2.5c-2.5b	Parkhill-Londo loams
	15	4/2b-2.5b	Iosco-Londo association
	11	4/2b-5b	Iosco-Au Gres sands
	20	others	

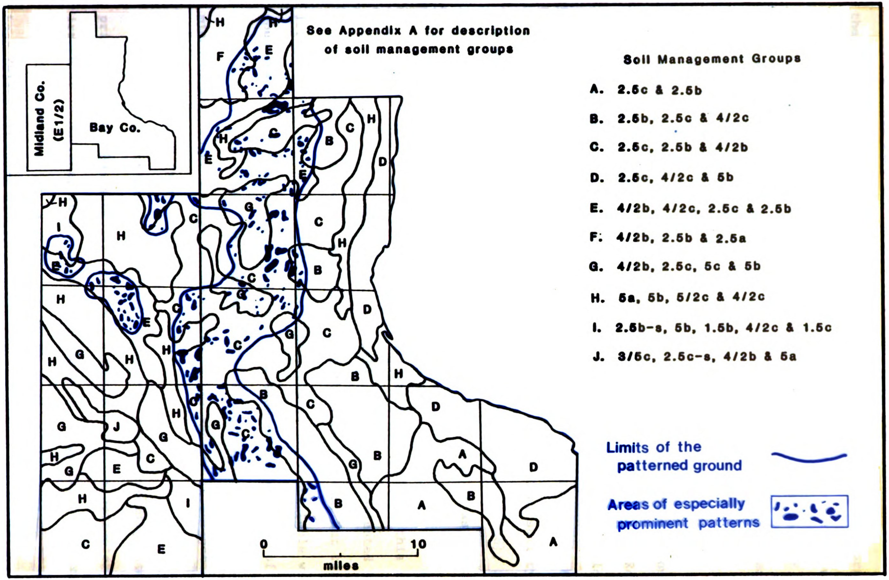
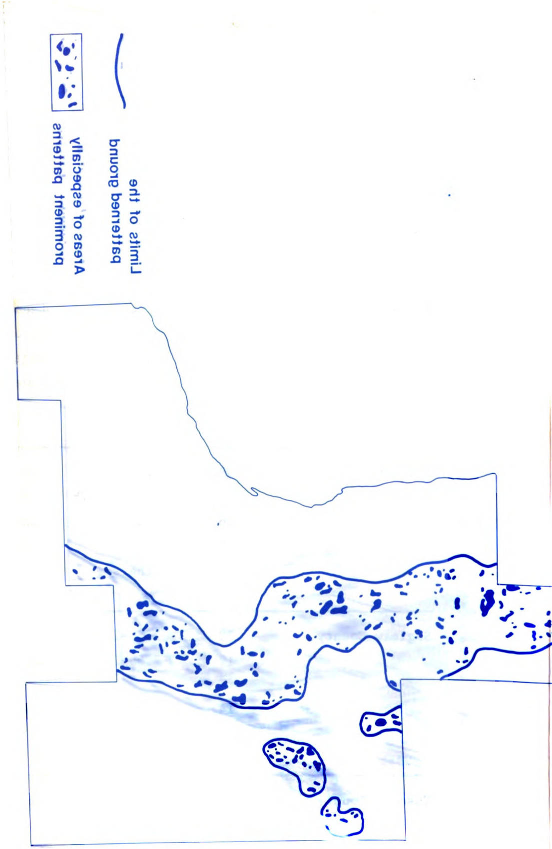


Figure 23. Soil associations and patterned ground distribution in Bay County and eastern Midland County.


Limits of the patterned ground
Areas of especially prominent patterns

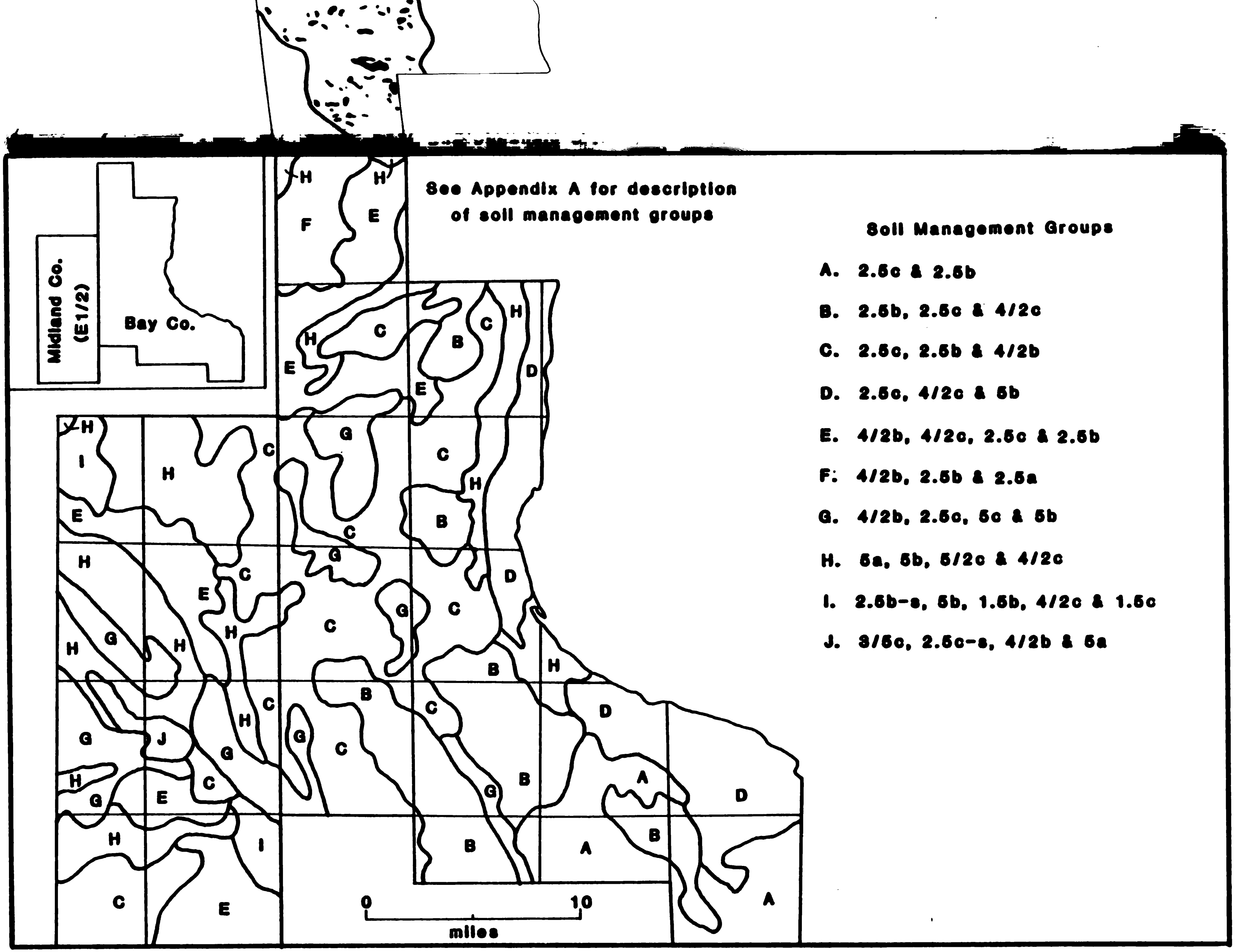


Figure 23. Soil associations and patterned ground distribution in Bay County and eastern Midland County.

As a rule, patterned ground is not found on well-drained sites in the Saginaw Lowland, nor is it associated with coarse-textured or organic soils. Patterns which occur in areas of coarse surface texture are usually underlain by finer-textured sediments within less than three feet of the surface. Most of these two-storied soils consist of lacustrine or eolian sands deposited over till. Conspicuous patterning in the study area is rare on clay loam or clay soils.

In east-central Saginaw County, a soil wedge, associated with one of the nonsorted nets, was observed in cross-section in a ditch along Reimer Road 3.5 mi east-northeast of Bridgeport (Figure 24). The site is located on a waterlain segment of the Port Huron Moraine at an elevation of 630 ft in nearly level terrain with slopes of 1% or less. The local soil type is Kawkawlin loam according to the 1933 soils map (Moon et al., 1938); in a recent revision, Mahjoory and Whiteside (1976) classified it as Capac-Parkhill loams.

Plate V shows the Bridgeport wedge exposed in the wall of this roadside ditch adjacent to an agricultural field. Its axis is oriented nearly vertical and the wedge-form extends to a depth of about 2.1m, but tapers irregularly (Plate VI). During excavation, the ground water table was encountered 20cm beneath the ditch floor and prevented the exposure of the basal apex of the wedge. The maximum depth of the wedge (2.1m) was determined by soil auger borings in the bottom of the pit and is subject to an error of not more than ±8-10cm.

The Bridgeport wedge is differentiated from the surrounding material primarily on the basis of its texture. Although the wedge perimeter is irregular in outline, it nevertheless defines an abrupt textural change from the coarse sediments within the wedge to the finer material of the host (Plate VII). As Figure 25 indicates, the wedge is composed of a

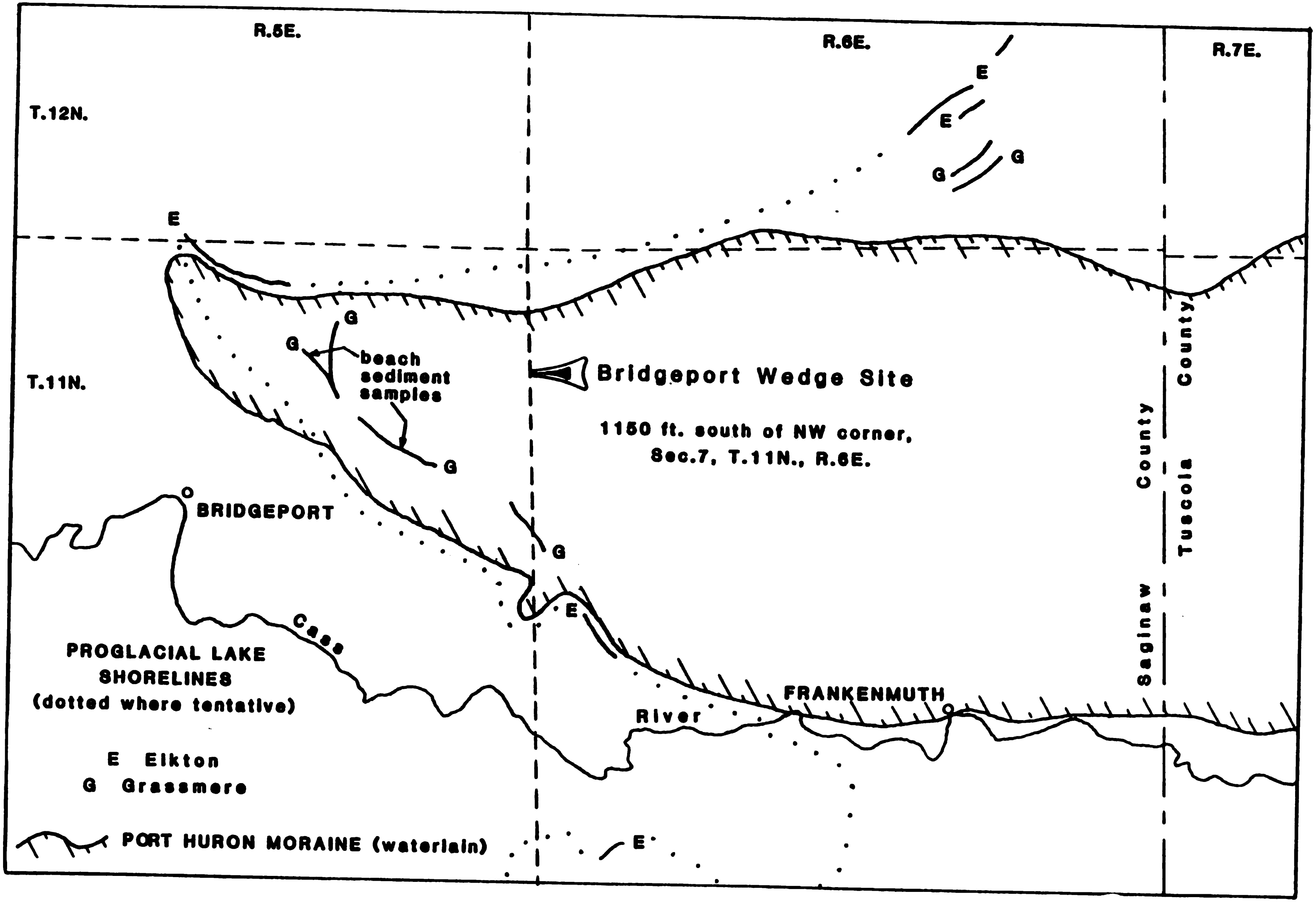
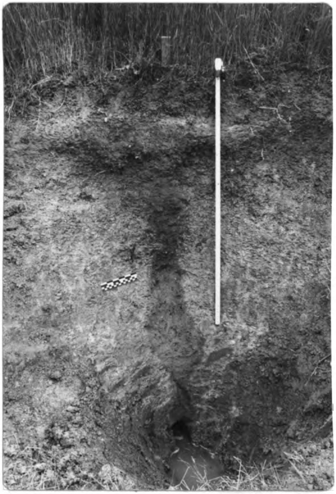


Figure 24. Site and situation of the Bridgeport wedge.

(tape measure length = 1m)

Plate V. View of the Bridgeport wedge exposure, looking southeast.



(tape measure length = 1m)

Plate VI. The Bridgeport exposure showing the irregularly downward-tapering wedge.

(scale = 15cm)

Plate VII. Lower portion of the Bridgeport wedge showing its irregular, but abrupt perimeter and its basal width exposed by groundwater piping away the sandy wedge-infill material.

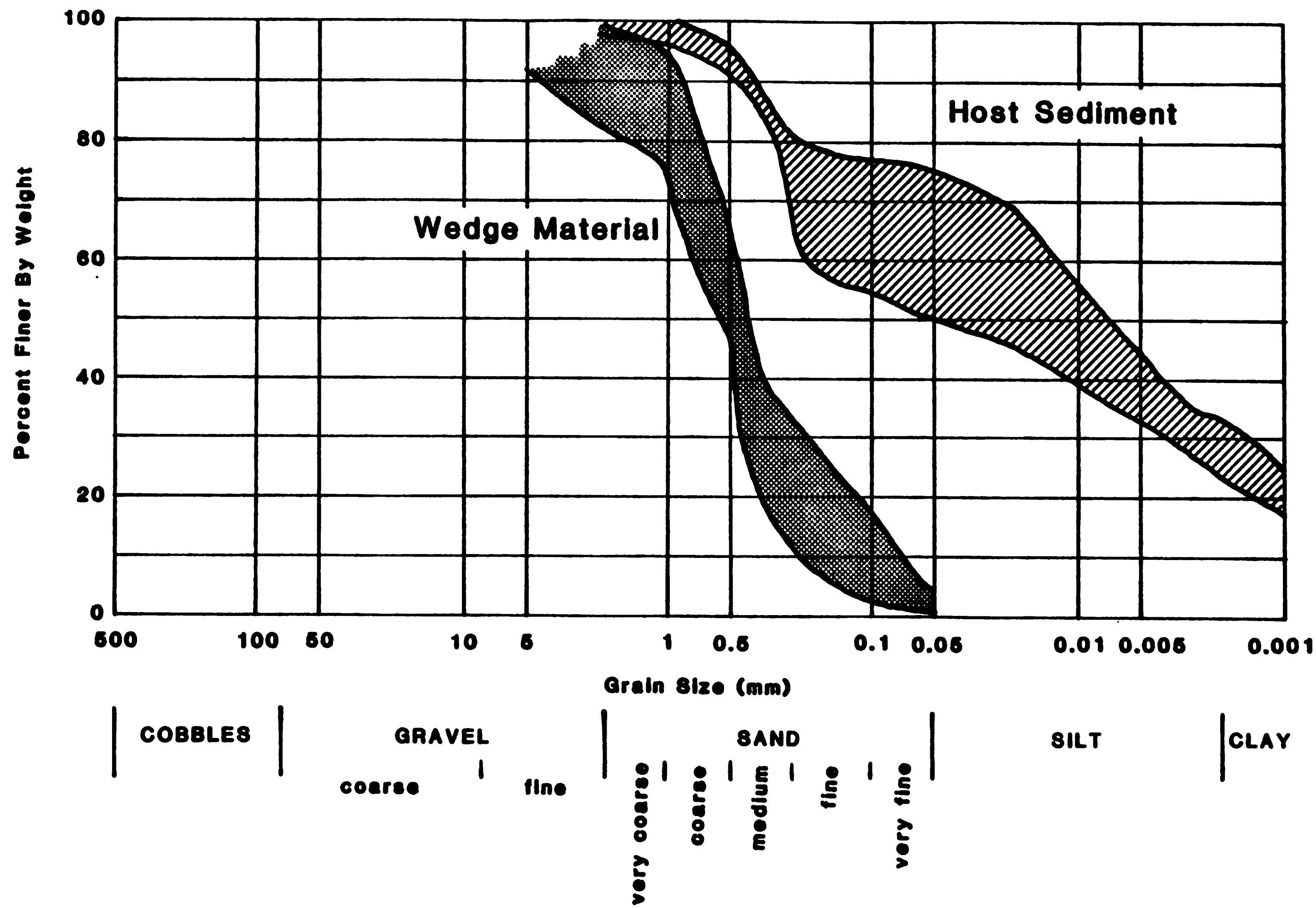


Figure 25. Composite cumulative grain-size frequency curve showing the range of particle sizes associated with both wedge-infill and host sediments.

medium sand (median diameter = 0.47mm), in stark textural contrast to the adjacent sandy clay loam to clay loam host material (median diameter = 0.017mm). Less than 5% of the wedge sediment is finer than 0.5mm, but the surrounding regolith consists of 50 to 75% silt and clay.

The clay loam parent material of the host contains 1% or less gravel-size particles, but is, nevertheless, poorly sorted (sorting coefficient = 8.3)[4] and appears to be a glacial till. By comparison, up to nearly 20% of the well-sorted wedge material (sorting coefficient - 1.8) is composed of coarse fragments (≥ 2mm). Neither of these sediments display any bedding or stratification.

Since the wedge site is located downwind (east) from two Grassmere beach ridges, the possibility existed that these beach deposits were the source areas of the wedge infill material. To investigate this hypothesis, particle size analyses were conducted on two samples taken at a depth of three feet from these littoral accumulations (see Figure 24, p. 63). As shown in Figure 26, the beach material is a very well-sorted fine sand (sorting coefficient = 1.26; median diameter = 0.15mm). Although some of this fine beach sand could have been transported to the wedge site by eolian activity, it does not constitute the majority of the infilling sediment.

The three-dimensional nature of the Bridgeport wedge was revealed by the continuation of its truncated basal segment for a distance of 1.5m across the floor of the drainage ditch (Plate VIII). The local strike of the wedge axis is S 79° W. The wedge pinched out abruptly prior to

[4]The sorting coefficient (S_o), developed by Trask (1932), is a measure of the spread of a grain-size distribution; the coefficient becomes larger as the sorting becomes poorer. It is defined as the square root of the ratio of the 25% quartile value to the 75% quartile value. Well sorted sediments have S_o values less than 2.5, moderately sorted materials have S_o values ranging from 2.5 to 4.0 and poorly sorted deposits have S_o values larger than 4.0 (Krumbein and Sloss, 1963).

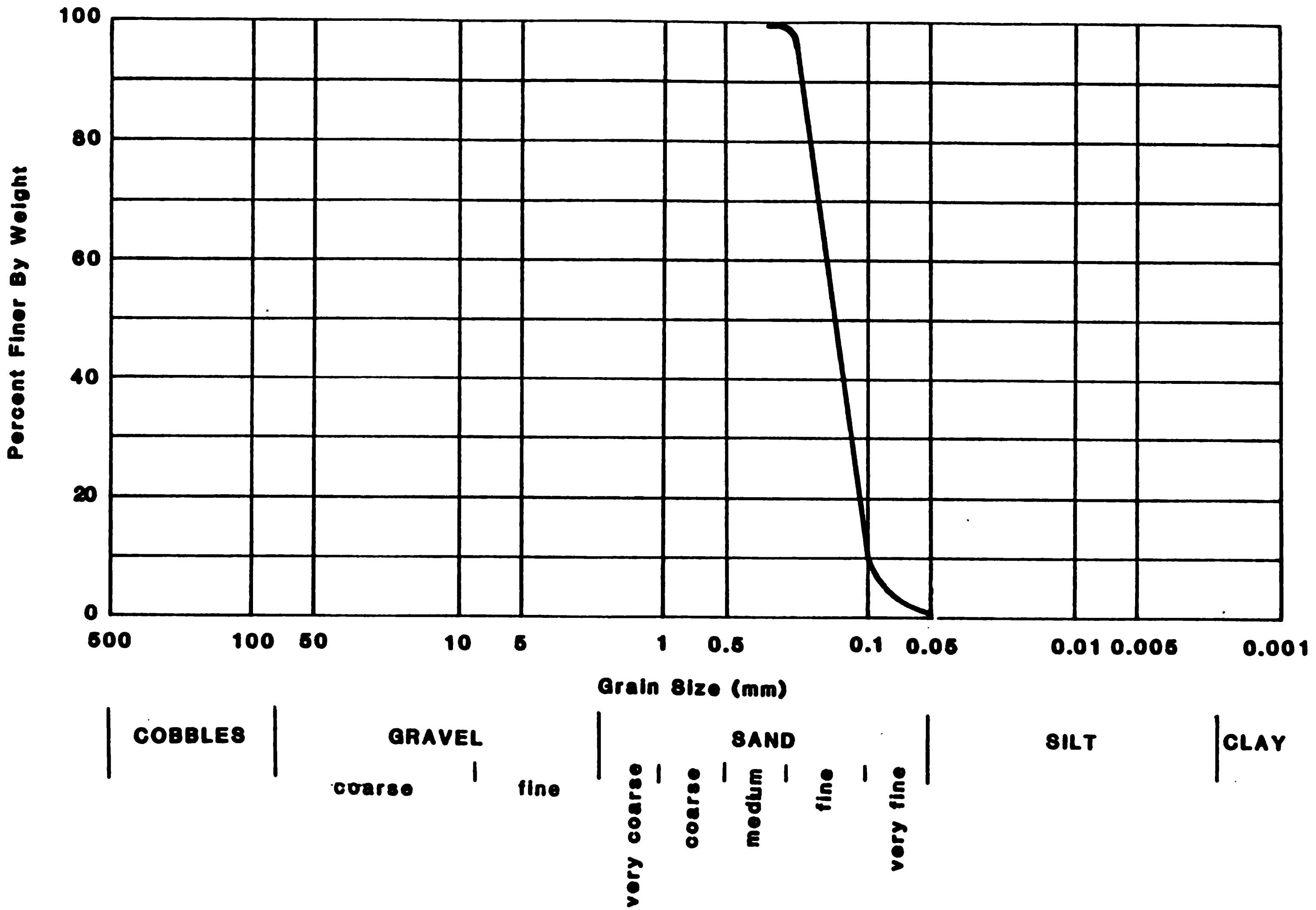


Figure 26. Cumulative grain-size distribution of the sediment from two beach ridges associated with glacial Lake Grassmere.

(tape measure length = 1m; scale = 15cm)

Plate VIII. Bridgeport wedge exposed in the ditch wall and the continuation of its truncated basal section across the floor of the ditch.

reaching the opposite ditch wall and did not crop out in the drainage ditch on the west side of Reimer Road; it did, however, extend back into the slope behind its exposed face for at least 3 to 4m, as determined by auger borings and electrical resistivity surveys. The partial apparent resistivity curve shown in Figure 27 reveals the presence of the soil wedge at station 6 and shows it to be a zone of relatively high conductivity.

In north-central Saginaw County, well-expressed nonsorted nets near Lawndale, Michigan occur on the same soil types (Capac-Parkhill loams), with similar topographic conditions (elevation = 630 ft; slope < 20 ft/mi) and in the same geomorphic setting (proximal slope of a waterlain segment of the Port Huron Moraine) as those at the Bridgeport site (Figure 28). The soil conditions underlying the mesh of one of the largest and most conspicuous of these patterns (shown at "A" in Figure 20, p. 54) were studied. As shown in Figure 29, the auger borings made at this site revealed that two-storied soils are dominant within the relatively narrow mesh zone along the north and west margins of the nonsorted net. The majority of these samples consist of 30" to 48" of sand overlying loam to sandy clay loam till. In several places, the sand layer exceeds five feet in thickness. On the south and east borders of this net cell, as well as within the area enclosed by the mesh, the soil parent material is loam to sandy clay loam till.

Figure 30 depicts the soil profiles exposed in the three pit excavations. The thickness of the superjacent sand deposit decreases toward the west, away from the center of the mesh zone, and its texture grades from a well sorted, medium sand (sorting coefficient = 1.68; median diameter = 0.28mm) to a moderately sorted, very fine sand (sorting coefficient = 2.5; median diameter = 0.09mm) in the same direction. As exposed in Pit 3,

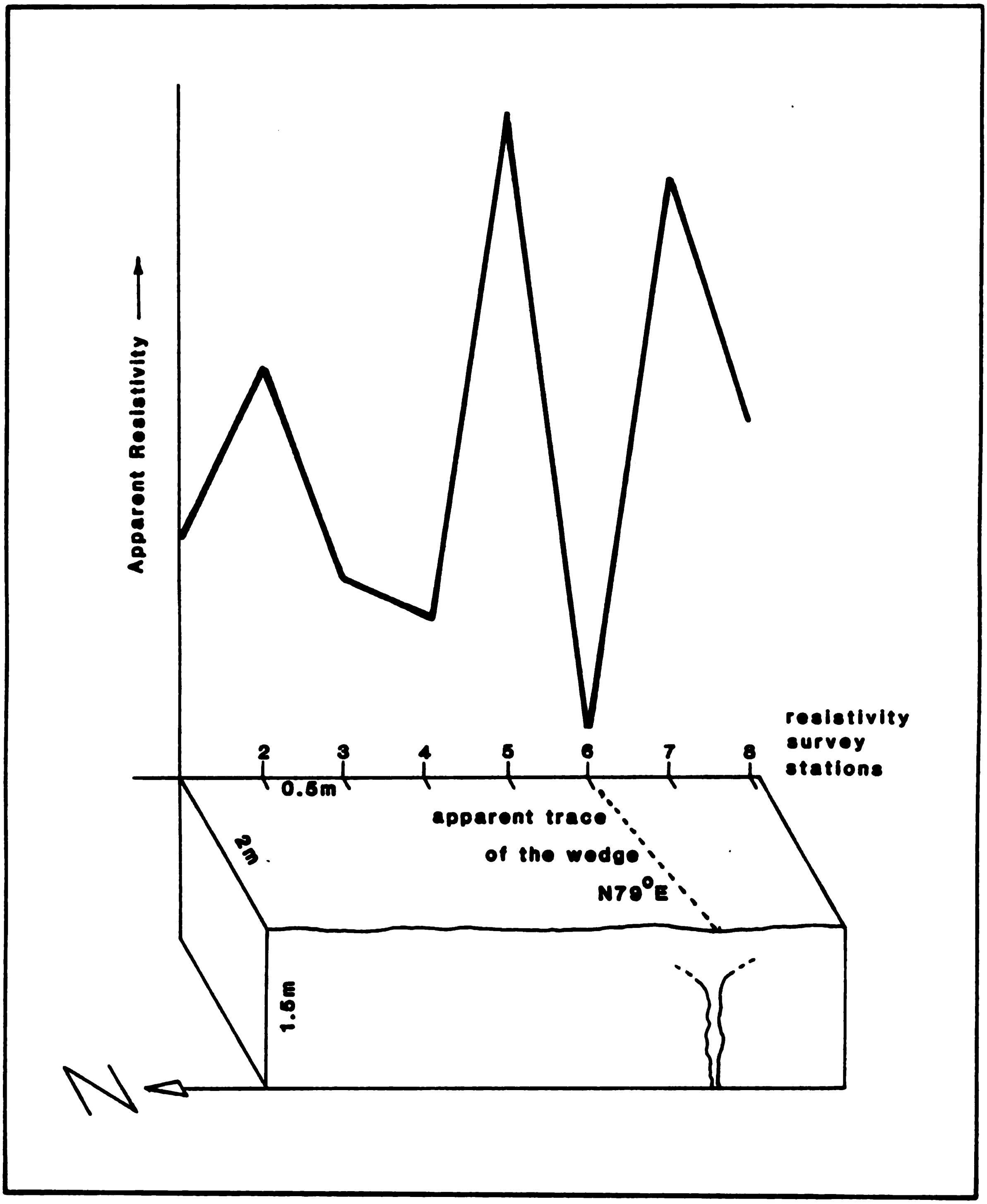


Figure 27. Electrical resistivity profile showing the conductivity anomaly associated with the subsurface continuation of the Bridgeport wedge.

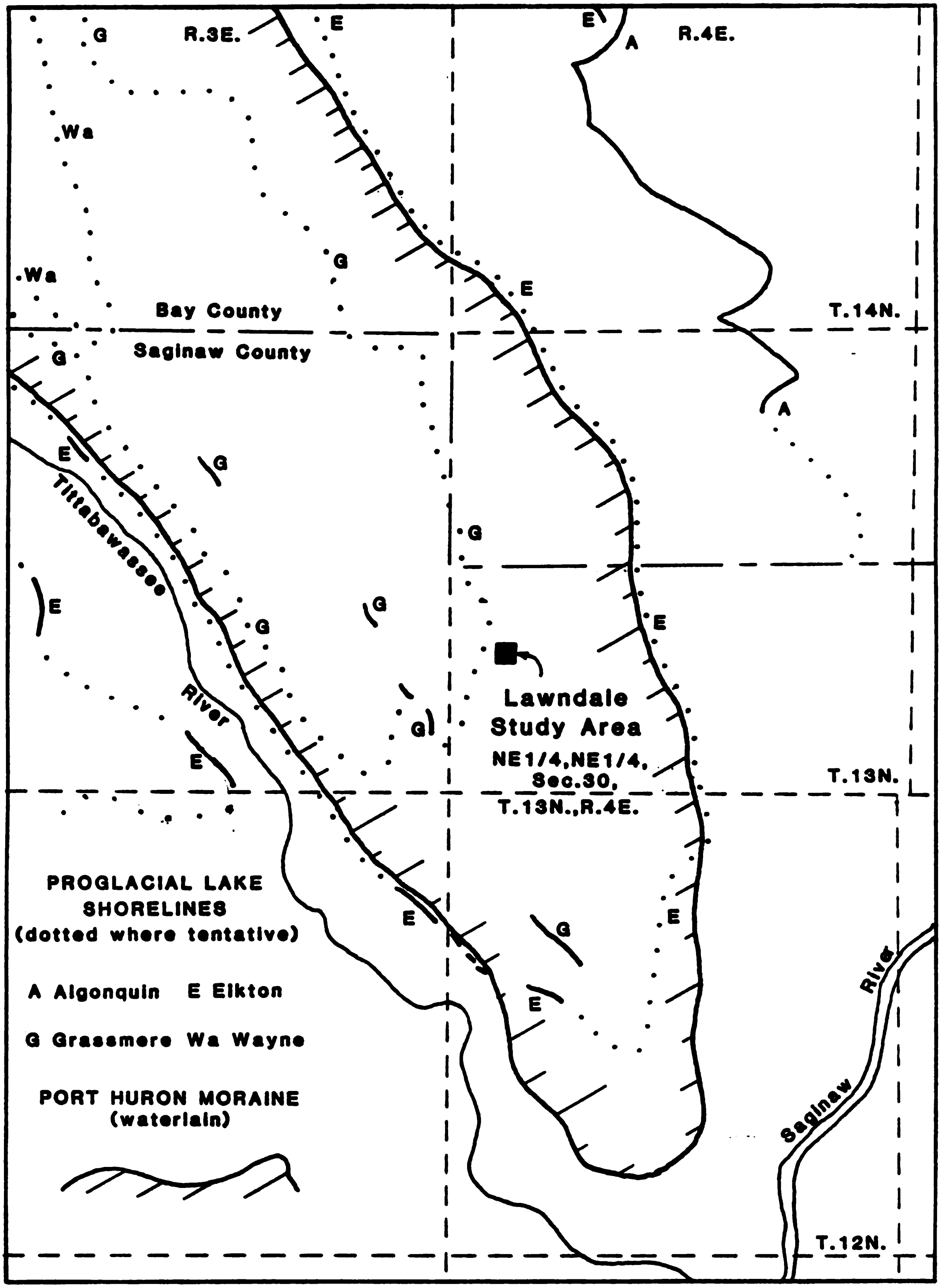


Figure 28. Site and situation of the Lawndale study area.

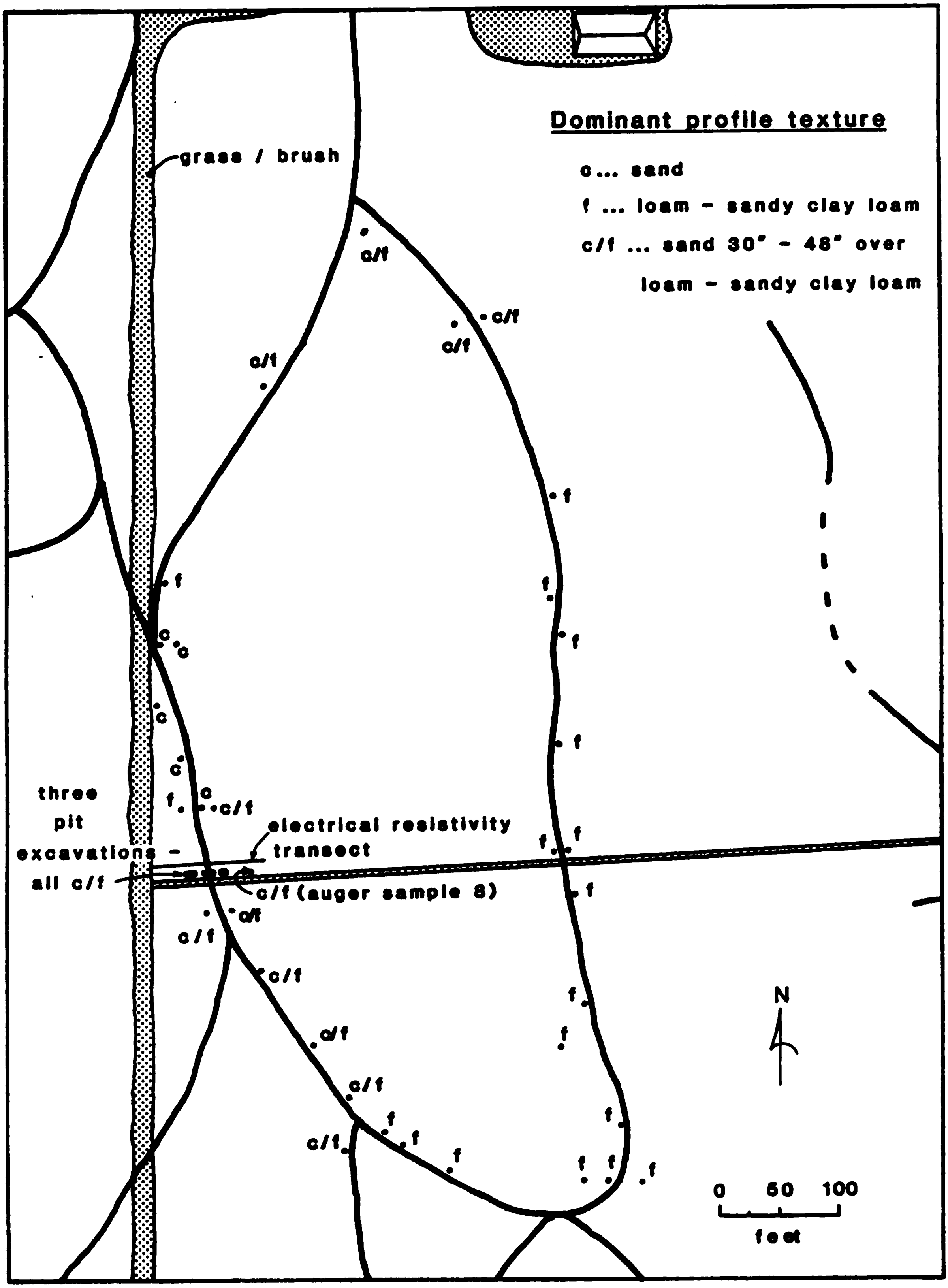


Figure 29. Dominant soil profile textures associated with the mesh of the Lawndale nonsorted net cell.

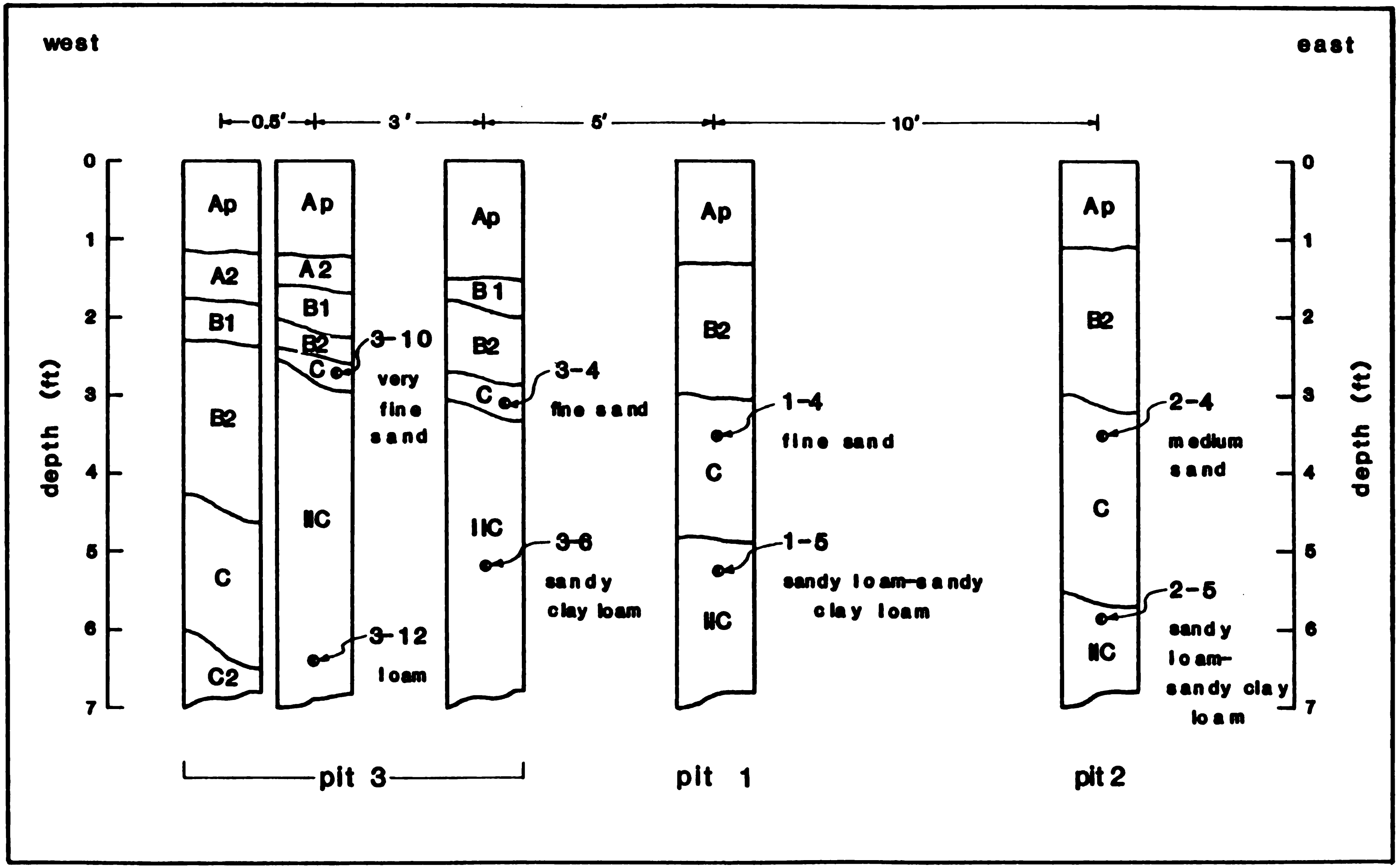


Figure 30. Soil profiles of the three pit excavations at the Lawndale site showing the stratigraphic positions of the samples taken for particle size analyses.

this sand layer pinched-out abruptly along its western edge. Nowhere within the three pit exposures did the sand deposit exhibit any structures, bedding or stratitification. The underlying till varied in texture from loam to sandy clay loam and the boundary between it and the overlying sand was smooth and abrupt, occurring within a vertical distance of no more than 3cm. Figure 31 presents the results of the particle size analyses of the eight soil samples whose stratigraphic positions are shown in Figure 30 (p. 75).

Figure 32 shows the resistivity profile along the transect located 3 ft north of the excavations in comparison with the textural data from the three pits and auger sample 8. These resistivity data can be interpreted to indicate: 1) a positive resistivity anomaly is associated with the sand layer overlying the till; 2) the two-storied soil exposed in the three excavations and detected in auger sample 8 appears to be continuous between these locations; and 3) the width of the sand deposit, which is correlated with the mesh zone of the net, is about 50 ft. The abrupt change in electrical resistivity associated with both the eastern and western mesh margins is probably indicative of the rapid thinning of the sand deposit at these locations. The lower conductivity of this material compared to the adjacent finer-textured till can be attributed to its increased porosity and decreased water holding capacity.

The Topographic Setting

As a physiographic region, the Saginaw Lowland is characterized by gentle slopes and subtle local relief. Notable exceptions to this generalization are located in northern Bay and central Tuscola counties where more rugged topography is associated with the subaerially deposited segments of the Port Huron Moraine. Other localized areas of steeply sloping terrain

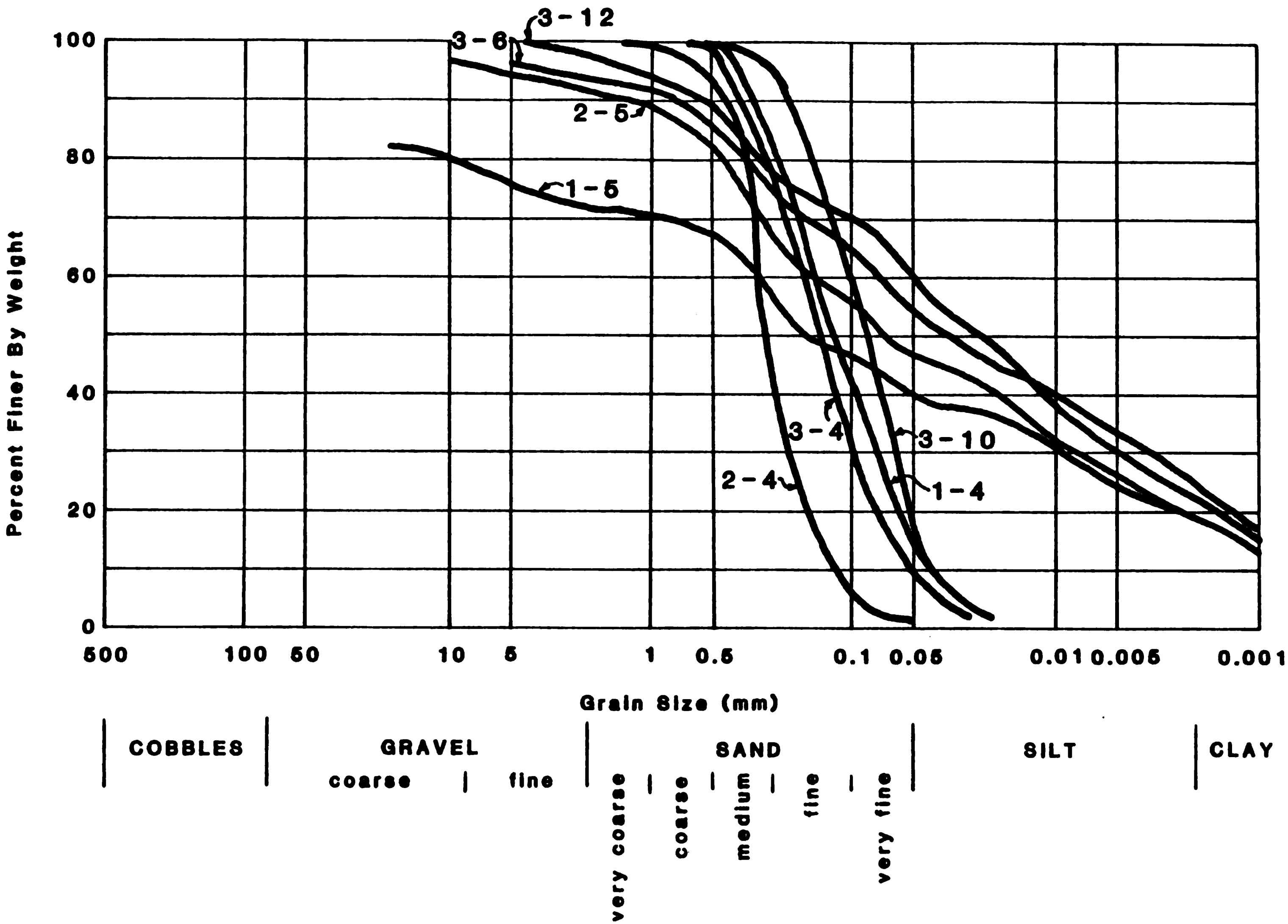


Figure 31. Cumulative grain-size frequency curves showing the contrasting parent materials at the Lawndale site.

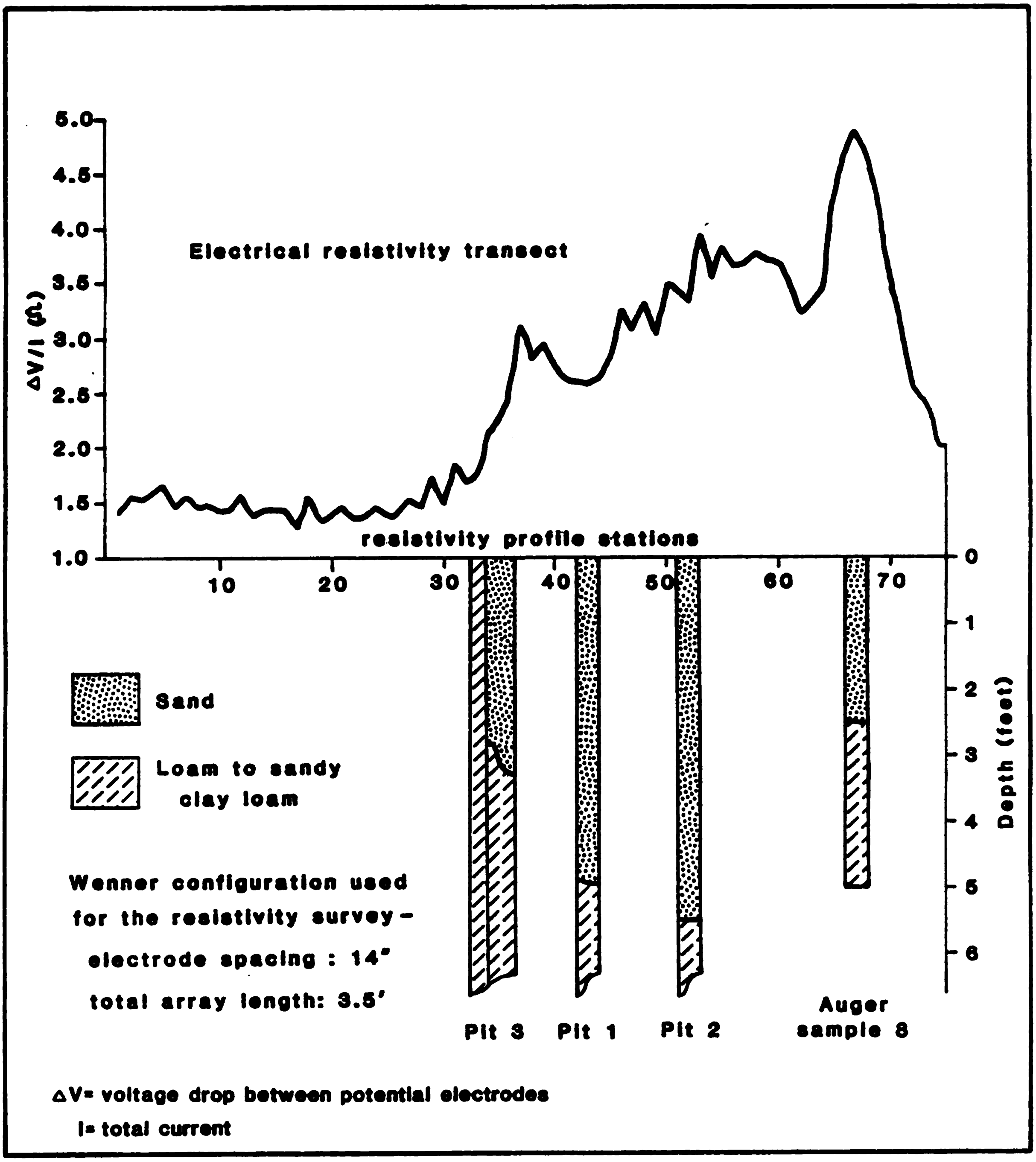


Figure 32. Electrical resistivity profile across the mesh zone of the Lawndale net compared to subsurface textural data.

and increased relief are found along the valleys of both the Tittabawassee and Cass rivers and on the distal margin of the Port Huron Moraine in the western part of the study area where large dunes are common.

The local relief in the general area of the patterned ground is shown in Figure 33. The nonsorted nets occur primarily on surfaces of low relief, as summarized in Table 6. Of the areas exhibiting conspicuous patterns, 83% have no more than 15 ft/mi^2 local relief. All of these sites slope less than 3% and a large proportion of them have less than 1% slope. Although 17% of the nets are located in survey sections having 20 ft or more of relief, these patterns usually occur on sites within these areas which slope less than 3% and are generally flat.

Table 6

Frequency of patterned ground by local relief category

Local Relief (ft/mi^2)	Frequency (%)
< 10	23
10–15	60
20–30	16
> 30	1

More than half of the patterned ground sites are found on terrain having 10–15 ft/mi2 relief. These areas tend to be composed of somewhat poorly drained drift, whereas poorly drained tracts usually have less than 10 ft/mi^2 local relief and well-drained sites typically attain 20 ft/mi^2 or more elevational change.

Elevations in the study area vary from 580 feet near the shore of Saginaw Bay to more than 980 feet in the morainic terrain of south-central Tuscola County. The highest point within the Port Huron Moraine in the

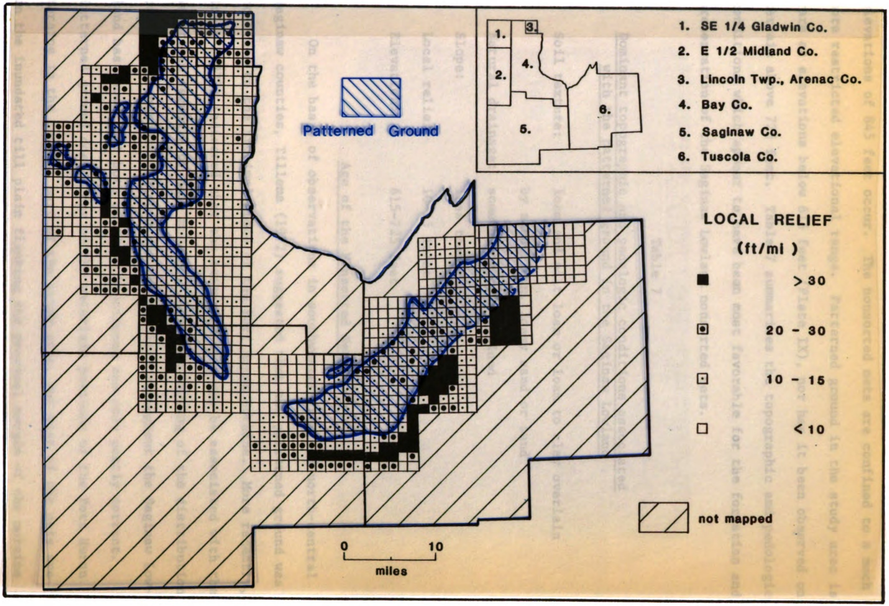
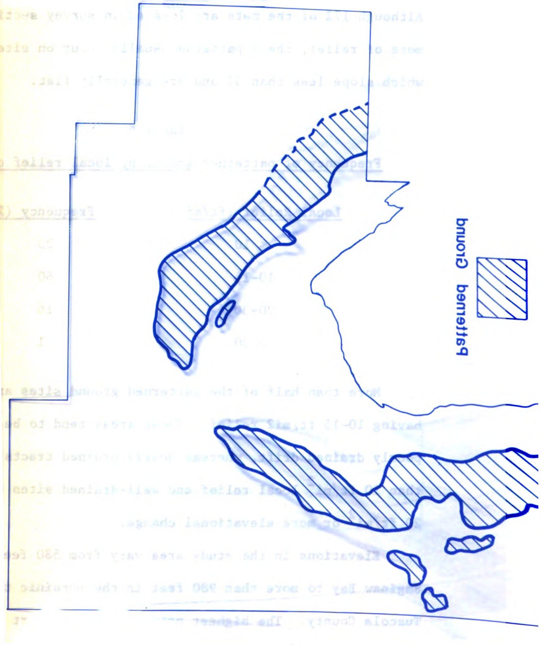


Figure 33. Local relief of patterned terrain in the Saginaw Lowland.


Patterned Ground

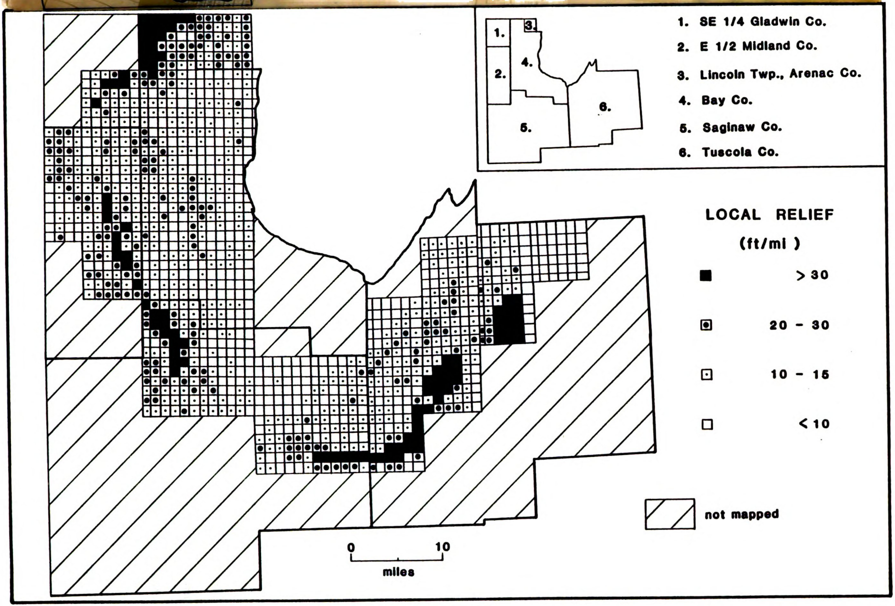


Figure 33. Local relief of patterned terrain in the Saginaw Lowland.

Saginaw Lowland is in Gibson Township, Bay County (T. 18 N, R. 3 E) where elevations of 845 feet occur. The nonsorted nets are confined to a much more restricted elevational range. Patterned ground in the study area is rare at elevations below 615 feet (Plate IX), nor has it been observed on terrain above 725 feet. Table 7 summarizes the topographic and pedologic conditions which appear to have been most favorable for the formation and/or preservation of the Saginaw Lowland nonsorted nets.

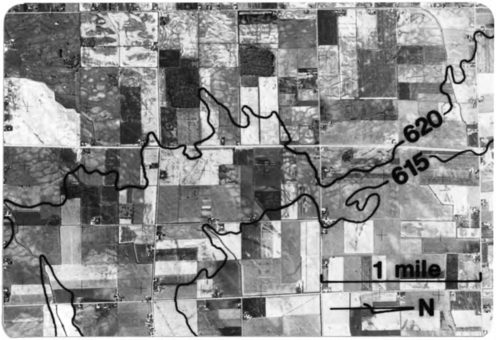
Table 7

Dominant topographic and pedologic conditions associated with the patterned ground in the Saginaw Lowland

Soil texture:	loam and silt loam or loam to clay overlain by sandy loam, loamy sand or sand
Natural drainage:	somewhat poorly drained
Slope:	less than 3%
Local relief:	10-15 ft/mi^2
Elevation:	615-725 feet

Age of the Nonsorted Nets

On the basis of observations in southwestern Bay and north-central Saginaw counties, Tillema (1972) suggested that the patterned ground was confined to the proximal slope of the Port Huron Moraine. More recently, Lusch (1977) indicated that the nonsorted nets may be associated with the waterlain segments of this moraine. Detailed mapping of the distribution of both the patterned ground and the moraines throughout the Saginaw Lowland has shown that both of these hypotheses are only partly correct. Patterned ground does occur on the waterlain portions of the Port Huron Moraine in the central part of the study area, but most of the nets are on the inundated till plain flanking the proximal margin of the moraine



(NASA-JSC 309-22-143; May 13, 1975; Original in color)

Plate IX. Aerial view showing the lack of patterns below the 615 ft contour and conspicuous forms occurring only above 620 ft (Lake Elkton shoreline).

(Figure 34). Furthermore, two smaller areas of patterned ground are located beyond the distal edge of the Port Huron Moraine in northeastern Midland County. This spatial distribution indicates that the patterned ground post-dates the Port Huron readvance, i.e., it is younger than 13,000 yrs B.P. (see Table 3, p. 40). The similarities between the distal and proximal nonsorted nets and those which occur on the Port Huron Moraine suggest that all the patterns formed penecontemporaneously.

A more precise estimate of the age of the patterned ground may be derived from an analysis of the spatial relationship between the limits of patterning and the shorelines of the proglacial lakes, a method which was successfully used in southwestern Sweden (Svensson, 1973). Noting the conformity between the lower limit of patterning and the elevation of Lake Elkton and the occurrence of nonsorted nets above and below the Lake Grassmere shoreline, Tillema (1972) concluded that the nonsorted nets were post-Lake Grassmere in age and had developed during the presumed 500-year existence of Lake Elkton.

Recent studies of the Late Wisconsinan chronology of the Great Lakes suggest that less than 350 years elapsed between the formation of Lake Warren I and the establishment of Early Lake Algonquin (Calkin and McAndrews, 1969; Clakin, 1970; Karrow et al., 1975). Six separate proglacial lake levels have been identified within this time interval: Warren I and II, Wayne, Warren III, Grassmere and Elkton. Obviously, the post-Grassmere period must have been considerably shorter than 350 years which brings into question such an age for the Saginaw Lowland nonsorted nets.

The congruence of the lower limit of patterned ground and the Elkton shoreline is unmistakable (Figure 35). The shoreline of Lake Elkton has been deformed by isostatic recovery in the northern parts of the study area from its horizontal elevation of 620 feet upwards to 640 feet. The

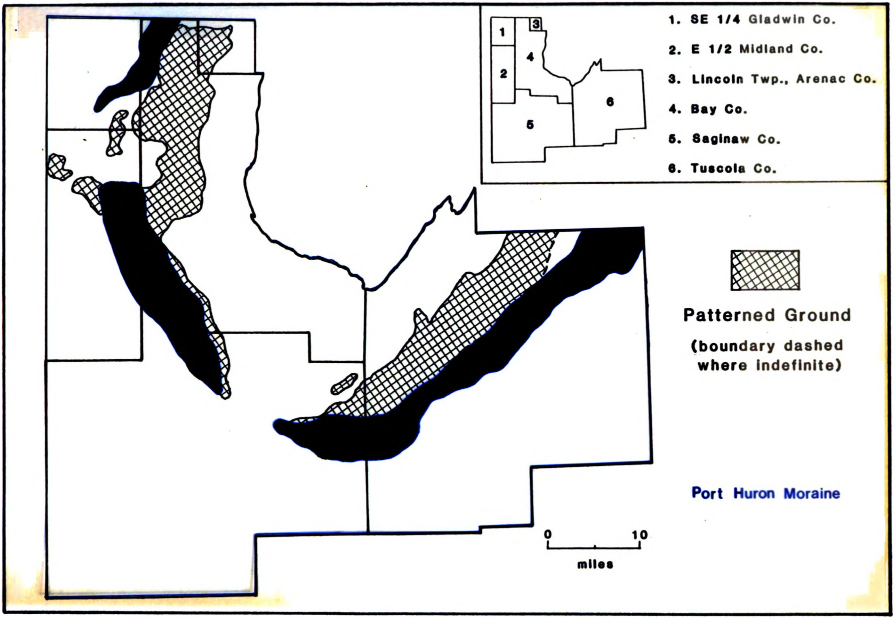
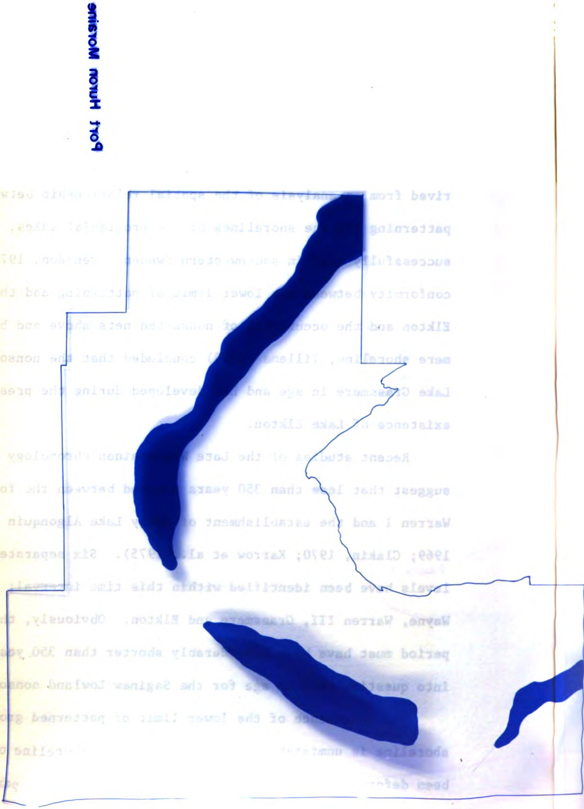


Figure 34. Spatial distribution of the Port Huron Moraine and the nonsorted nets in the Saginaw Lowland.


Port Huron Moraine

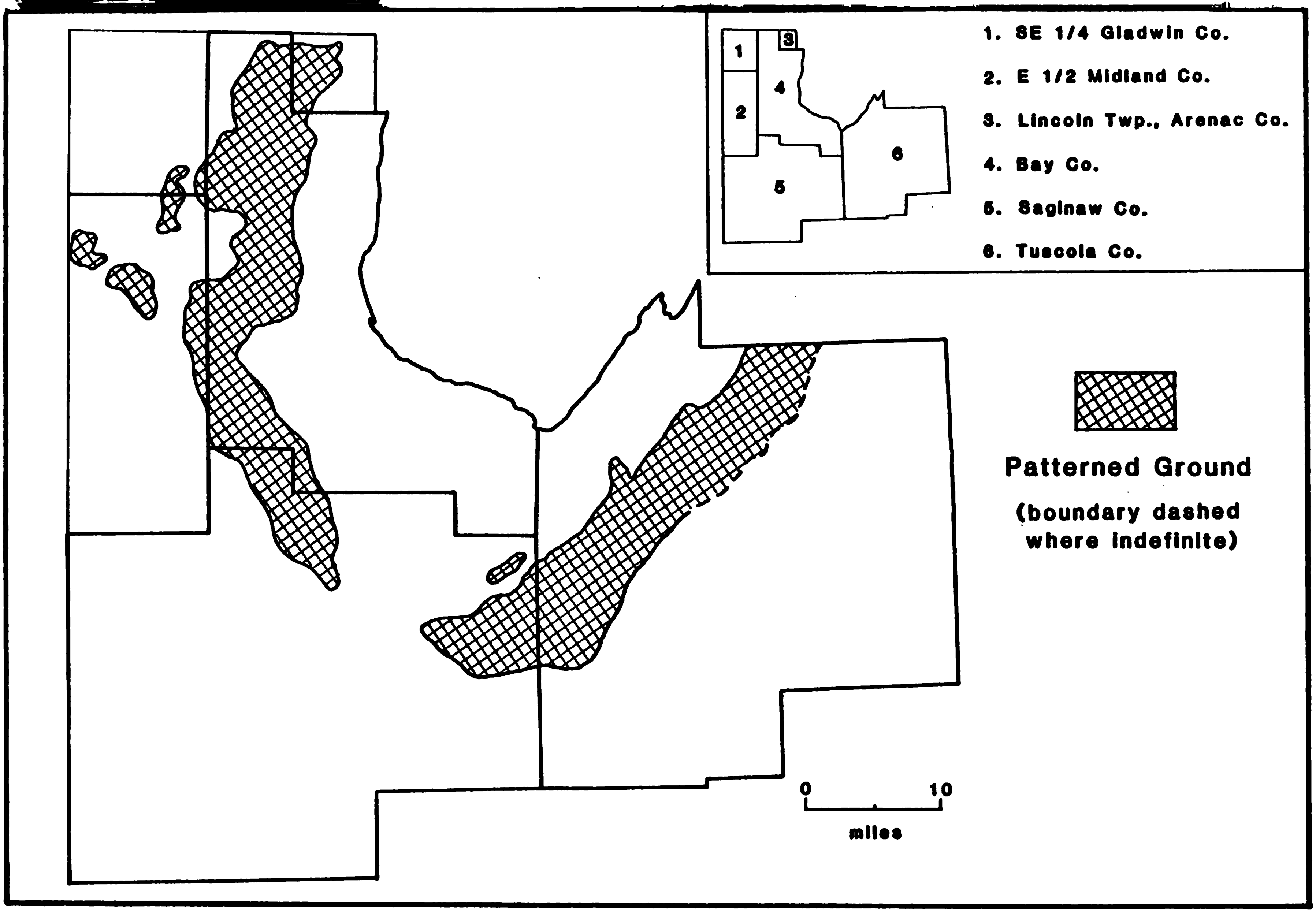


Figure 34. Spatial distribution of the Port Huron Moraine and the nonsorted nets in the Saginaw Lowland.

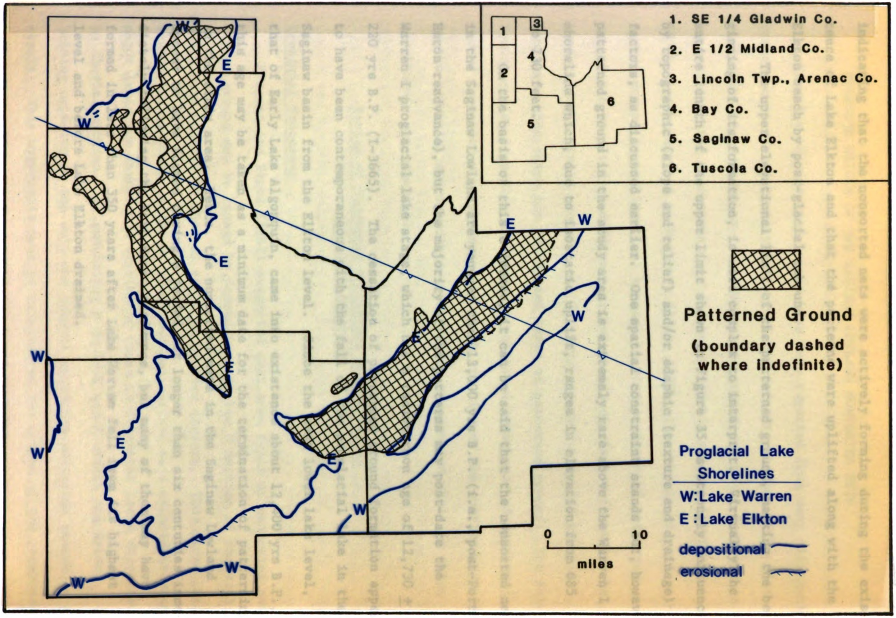
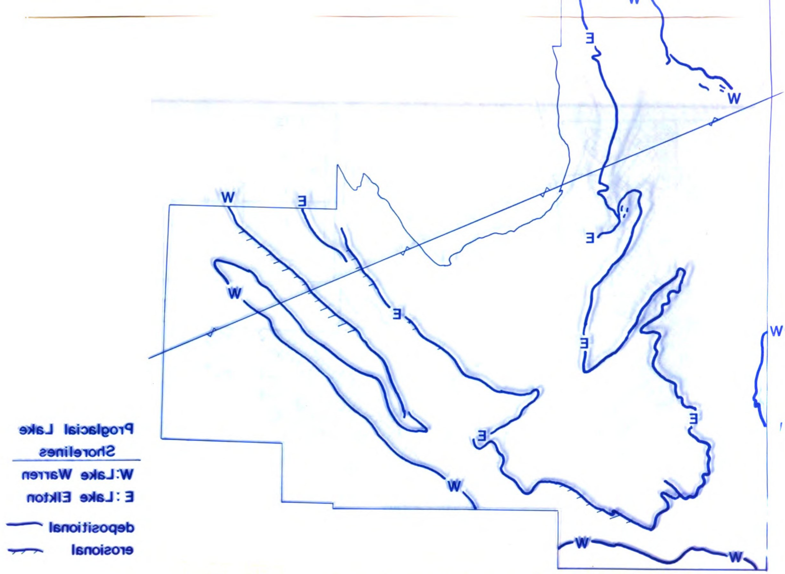


Figure 35. Distribution of the Saginaw patterned ground and the shorelines of Lake Elkton and Lake Warren.



Proglacial Lake
Shorelines
W: Lake Warren
E : Lake Elkton
depositional
erosional
W
E

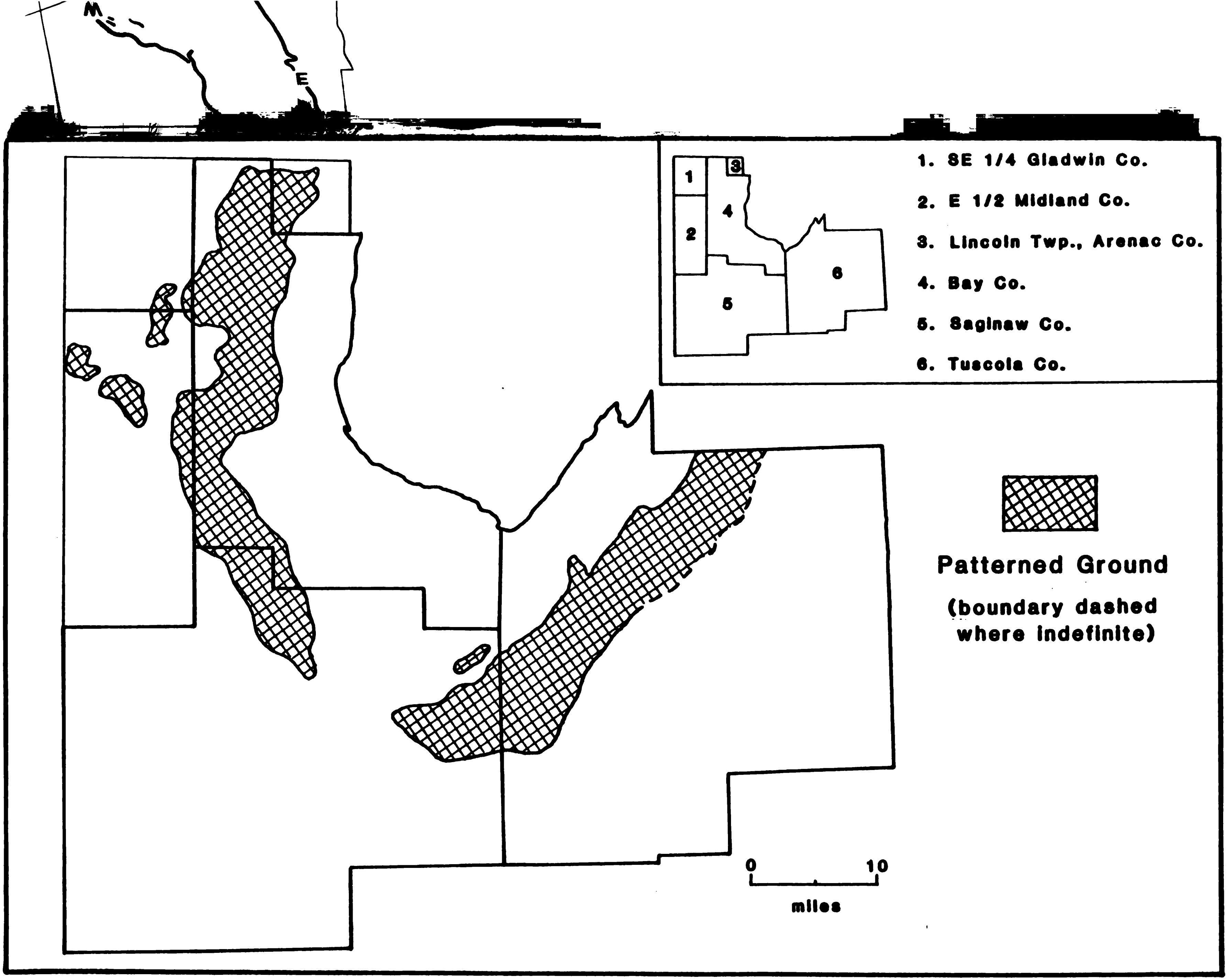


Figure 35. Distribution of the Saginaw patterned ground and the shorelines of Lake Elkton and Lake Warren.

lower elevational limit of the patterned ground follows this deformed line, indicating that the nonsorted nets were actively forming during the existence of Lake Elkton and that the patterns were uplifted along with the Elkton beach by post-glacial rebound.

The upper elevational limit of the patterned ground, marking the beginning of its formation, is more complex to interpret. Virtually the entire length of the upper limit shown in Figure 35 is strongly influenced by topographic (slope and relief) and/or edaphic (texture and drainage) factors, as discussed earlier. One spatial constraint stands out, however: patterned ground in the study area is extremely rare above the Warren I shoreline which, due to isostatic uplift, ranges in elevation from 685 to 730 feet.

On the basis of this evidence, it can be said that the nonsorted nets in the Saginaw Lowland are younger than 13,000 yrs B.P. (i.e., post-Port Huron readvance), but the majority of the patterns may post-date the Warren I proglacial lake stage, which has a radiocarbon age of 12,730 $\pm$ 220 yrs B.P. (I-3665). The cessation of patterned ground formation appears to have been contemporaneous with the fall of the proglacial lake in the Saginaw basin from the Elkton level. Since the next lower lake level, that of Early Lake Algonquin, came into existence about 12,400 yrs B.P., this age may be taken as a minimum date for the termination of patterning in the study area. Hence, the nonsorted nets in the Saginaw Lowland appear to have formed during a period not longer than six centuries immediately following the Port Huron readvance, but many of them may have formed in less than 350 years after Lake Warren fell from its highest level and before Lake Elkton drained.

CHAPTER IV

PROPOSED ORIGIN OF THE SAGINAW LOWLAND NONSORTED NETS

Examples of patterned ground have been reported from many different environments of widely varying thermal and moisture regimes. The identification of inactive or fossil patterned ground can be of great value in environmental reconstructions and paleoclimatic studies (Washburn, 1973). As summarized by Washburn (1956, 1970), the genesis of most patterned ground is problematical because 1) similar forms of patterned ground can result from different processes; 2) dissimilar forms can be produced by a single process; and 3) there are more proposed genetic processes than there are recognized types of patterned ground. The following review separates the numerous published hypotheses of patterned ground formation into processes in which cracking of the surface regolith is the essential and immediate cause of the pattern and those in which cracking is non-essential.

Review of Suggested Mechanisms Not Requiring Regolith Cracking

Erosional Processes

Presant and Protz (1967) suggested that some types of nonsorted patterned ground may be caused by depressions in the B horizon of the soil which were related to channel scour in braided streams. They found that trends in the micro-relief of the B horizon surface were coincident with major landscape trends and attributed these coincidental trend directions to fluvial erosion. An undulating B horizon could affect the water holding capacity of the soil and produce nonsorted patterned ground as a result. This hypothesis must be rejected as the origin of the nonsorted nets in the study area because 1) the trends of the patterns are not coincident with topographic trends; 2) the depth of the B horizon surface is not consistently depressed along the net mesh; and 3) this mechanism cannot produce unstratified soil wedges such as the one at the Bridgeport site.

Morgan (1972) considered surficial drainage along fractures in till as a possible origin for nonsorted polygons. These fractures were related to the ice movement and some of the observed patterns were aligned nearly parallel to this direction. In the Saginaw Lowland, this origin is untenable because trends in the net mesh are unrelated to either ice flow direction or surface drainage. Additionally, fluvial processes could not account for the narrow, unstratified soil wedge such as that exposed at the Bridgeport site.

Pedologic Processes

The similarity between soil tongues and certain types of patterned ground was the first reported by Yehle (1954). More recently, White (1971) and Byrne (1975) have investigated similar phenomena in South Dakota and Ontario, respectively. These pedologic features result from differential solution by percolating soil water and are common in sandy gravel deposits. They are also well developed in the Fox soil series which is composed of loamy sediments overlying sand and gravel. The Saginaw patterns, on the other hand, formed on soils having much finer dominant textures. Soil tongues and related features can have a surface expression, but their mesh dimensions are usually less than 10 feet across, in contrast to the significantly larger cell diameters of the nets in the study area. Additionally, these in situ edaphic processes are incapable of producing the significant textural differences between the host material and the wedge infilling which were observed at the Bridgeport site.

Bedrock Control

Striking examples of nonsorted patterned ground have been reported from southern England (Perrin, 1963). Here, polygonal and elongated patterned ground was formed on thin drift underlain by chalk. The surficial patterns were associated with a ridge-and-trough micro-topography on the upper surface of the bedrock which was attributed to periglacial disturbances. Most of the drift in the Saginaw Lowland is more than 100 feet thick and it is extremely unlikely that bedrock micro-topography or jointing would be revealed as surficial nonsorted nets through such a drift thickness.

Glacial Stagnation Processes

The geometry, size and marking of the Saginaw pattern network show a certain similarity to ice stagnation landforms such as those reported by Gravenor and Kupsch (1959) and, even more so, to the photo pattern of hummocky ground moraine discussed by Parizek (1969). That the patterned ground in the study area is unrelated to glacial stagnation processes is demonstrated by its distribution distal to, on the surface of, and proximal to the Port Huron Moraine, as well as the lack of any other landform indicators of ice stagnation in the region. The low relief of the Saginaw patterned ground and the conformity of its lower elevational limit with a proglacial lakeshore also argues against a stagnation origin for these features.

Review of Suggested Mechanisms Requiring Regolith Cracking

Thawing

Thawing of regolith, whether seasonally or perennially frozen, has not been sufficiently investigated as a potential cause of nonsorted patterned ground but, according to Washburn (1973), this mechanism lacks convincing evidence. Black (1976) has suggested that thawing of buried ice blocks could produce nonsorted patterns. These "kettle cracks" form in the outwash which may inundate stagnant ice blocks. All the patterns observed in the Saginaw Lowland occur on much finer drift and their extent and geometric regularity are inconsistent with this proposed origin.

Synaeresis

According to Kostyaev (1969), synaeresis cracks can form polygons which are tens of meters in diameter. These fissures, resembling mud cracks, develop as water is expelled from a clay-rich suspension by internal forces. Synaeresis cracks probably determine the location of desiccation fissures but, as noted by Washburn (1973), they are relatively unimportant in forming nonsorted patterned ground. The larger size of the pattern mesh in the study area also precludes this mechanism as a possible origin.

Gilgai Development

Costin (1955) noted the striking similarity of surface patterns produced by gilgai development and classic frost-soil patterned ground. Gilgai soils form in response to volume changes resulting from desiccation and rehydration of regolith having a very coefficient of linear extensibility (Hallsworth et al., 1955). The swell potential of most soil series in the study area is usually less than 5%, well below the 30% swell capacity of typical gilgai soils. As a result, these Michigan soils are incapable of the shrink-swell volume changes necessary to produce large nonsorted nets.

Partial Wetting

Cracks formed by partially wetting regolith samples during laboratory experiments were reported by Corte and Higashi (1964) who suggested surface tension as their origin. The crude patterned ground formed by this unusual phenomenon is, however, of small mesh diameter, unlike the patterns in the study area. As with synaeresis cracks, these "wetting cracks" probably determine the location of subsequent desiccation fissures, but are unrelated to the Saginaw nonsorted nets.

Desiccation

One of the most common causes for the evolution of patterned ground is regolith contraction due to drying (Washburn, 1973). In fact, most well developed nonsorted polygons less than three feet in diameter are probably due to desiccation cracking (Tricart, 1969). There is also ample evidence, however, that desiccation can produce large-diameter patterned ground (Land, 1943; Wilden and Mabey, 1961; Chico, 1963, 1968; Neal and Motts, 1967; Neal, Langer and Kerr, 1968; Neal, 1972).

The similarity between the surface patterns produced by desiccation cracking and thermal contraction in permafrost has been noted by Knechtel (1951) and Black (1952a), but evidence of the long term, severe drought conditions necessary to form large dehydration polygons is lacking in the Saginaw Lowland. Quite to the contrary, most of the patterned ground in the study area occurs on somewhat poorly drained soils and it is likely that similar or more poorly drained conditions existed during the waning phase of the Late Wisconsinan, when several proglacial lakes occupied the Saginaw basin.

Dilation

Dilation cracking, resulting from local differential heaving or subsidence of the ground, is known to produce patterned ground (Benedict, 1970; Washburn, 1973), but crack networks of this kind have limited spatial extent and small mesh dimensions. Clearly, the large size and number of the Saginaw nets preclude dilation cracking as a cause for the patterns in the study area.

Salt Cracking

Large, nonsorted polygonal fissures in hard rock salt and desert salt crusts have been reported by Hunt and Washburn (1966). Although not completely understood, the genesis of these salt cracks seems to be thermal contraction. Considering the lithologic material involved, this process is obviously inapplicable to explain the reticulate patterns of the Saginaw Lowland.

Seasonal Frost-Cracking

Seasonal frost-crack polygons result from thermally induced contraction fissuring of seasonally frozen ground (Washburn, 1973). Active examples of this type of patterned ground have been reported from both arctic (Hopkins et al., 1955; Danilova, 1956; Friedman et al., 1971; Katasonov, 1973) and mid-latitude sites (Washburn, Smith and Goddard, 1963; Washburn, 1973; Black, 1976). There is some question, however, whether frost cracks in a seasonally frozen layer can be preserved in the geologic record, but Dylik (1966) and Pissart (1970) concluded that certain types of very narrow soil wedges are the pseudomorphs of seasonal frost fissues. Washburn

(1973) contends that fossil forms of these seasonal features would document such deep seasonal freezing that permafrost conditions were likely.

It is doubtful that the large-diameter reticulate pattern of the Saginaw nonsorted nets could have been formed by seasonal frost cracking, because the polygons produced by this process are usually less than 50 feet across (Shumskiy and Vtyurin, 1966). The Bridgeport wedge lacks the vertical bedding which Pissart (1970) considers to be characteristic of fossilized seasonal frost cracks and it is also much larger than the seasonal frost-fissure pseudomorphs reported from Europe.

Permafrost Cracking

Nonsorted patterned ground, formed by thermal contraction-fissuring in regions of perennially frozen ground, is one of the most common periglacial surface forms. According to Washburn (1973), this type of patterned ground is the most likely to be preserved and its fossil forms are of considerable significance because of their temperature implications. Thermally induced permafrost-cracking has been recognized since the early 19th century, but it was another hundred years before Leffingwell (1915, 1919) was able to scientifically explain the details of the process. Lachenbruch (1960, 1961, 1962, 1966) demonstrated that Leffingwell's hypothesis was theoretically sound and it has also been supported by field evidence (Kerfoot, 1972; Mackay, 1974).

Leffingwell proposed that, during the winter, thermal contraction of the regolith produces vertical fractures several millimeters wide which penetrate a few meters into the permafrost (Figure 36a). By the subsequent fall (Figure 36b), these cracks may be filled with meltwater, snow and/or hoarfrost, resulting in an ice vein (Mackay, 1975). Horizontal reexpansion of the warming permafrost during the summer can deform the

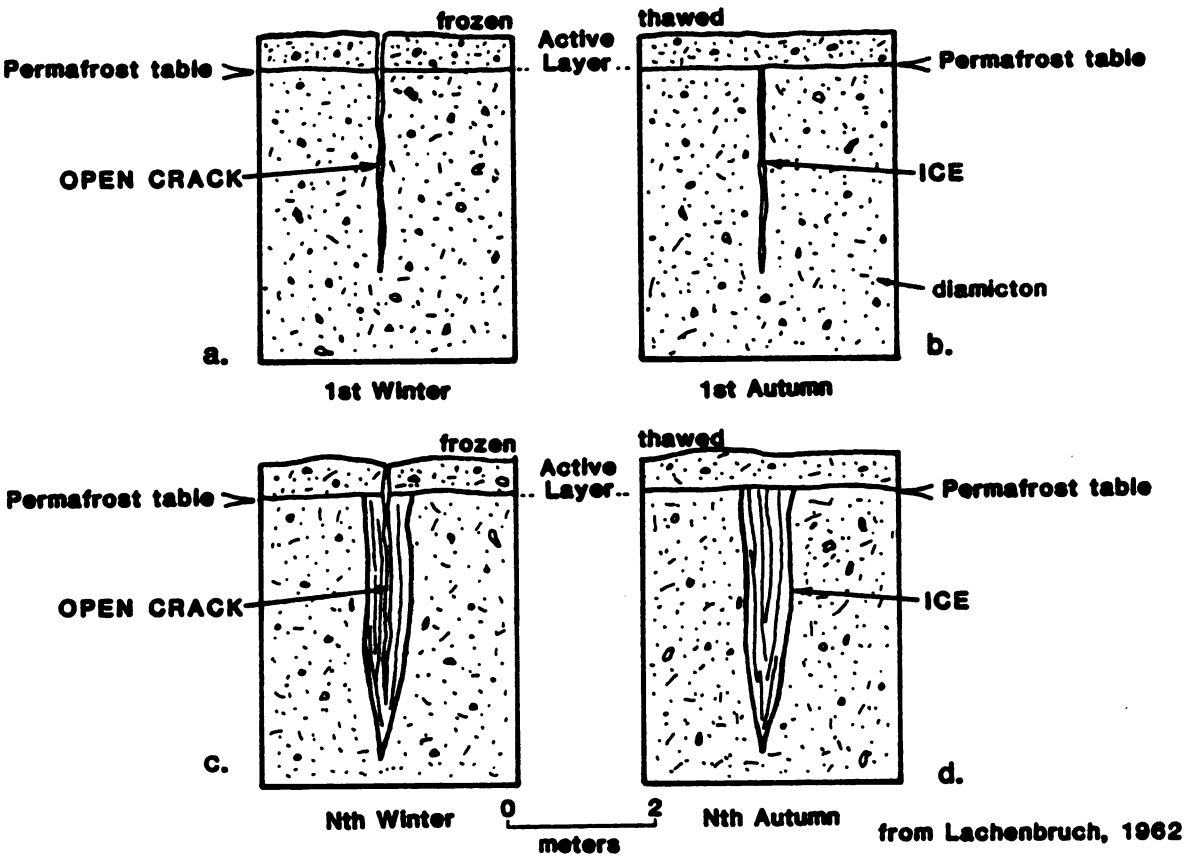


Figure 36. Thermal contraction-crack origin for ice wedges in permafrost.

frozen ground strata adjacent to these ice veins. These incipient ice wedges are zones of weakness in the permafrost and during subsequent freezing cycles renewed thermal tension will re-open the vertical, ice-cemented cracks (Figure 36c). Mature ice wedges result from a repetition of such cycles over a long period (Figure 36d). The natural surface form of tension cracks such as these is almost always polygonal and in active permafrost areas ice wedges underlie the polygonal mesh (Figure 37).

During the thermal degradation of permafrost, the enclosed ice wedges thaw or sublimate and the space they occupied can be replaced with adjacent, overlying or transported material (Péwé, Church and Andresen, 1969). Ice-wedge casts formed in this manner are often composed of sedimentary material which differs in texture, color and/or fabric from the surrounding host material. Although ice wedges are best developed in saturated (i.e., high ice content), fine-grained soil having little primary structure, these same edaphic conditions make it very difficult to preserve any evidence of their former presence (Black, 1976). The melting ice in the saturated permafrost promotes the rapid flowage and slumping of the fine-textured host sediment which can obliterate the wedge form if the ice wedge has not been replaced by transported material.

Johnsson (1959) presented the following criteria by which true ice-wedge casts could be identified:

1) The infill material of the supposed cast must have been deposited from above.
2) The host material surrounding the wedge case should display distorted strata due to pressure effects.
3) Elongated clasts in the host material should be preferentially aligned parallel to the axis of the pseudomorph.

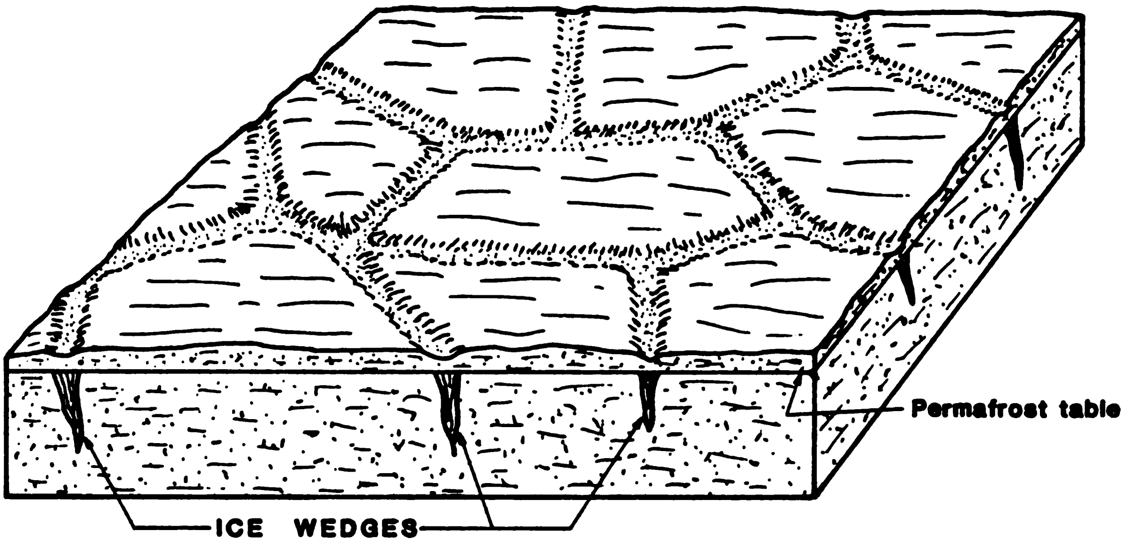


Figure 37. Relationship of ice wedges to ground patterning in active permafrost.

4) The ice-wedge cast should be triangular in shape, widest at the top and tapering with depth.

5) True ice-wedge pseudomorphs stand more or less vertically.

Other useful criteria for correctly identifying ice-wedge casts were suggested by Black (1976). He called attention to the need for supporting evidence of perennially frozen ground, such as a fossil permafrost table, and stated that biological indicators of frozen ground were only suggestive, not diagnostic. Black also stressed that the host material should be of a type that would be supersaturated under normal permafrost conditions and that multiple wedge casts should be present which form polygons in the plan view. Black reiterated the views of Johnsson (1959) with regard to the preservation of pressure effects and realigned clasts in the host material. Additionally, he proposed that slump fabrics in true ice-wedge pseudomorphs should show arcuate stratification (concave upward), in contrast to the near-vertical fabric of sand wedges.

Evidence Supporting An Ice-Wedge Origin for the Saginaw Nonsorted Nets

Data from the preceeding chapter strongly suggest that the Saginaw Lowland patterned ground was initially formed by permafrost cracking and ice-wedge development. The geometry of the reticulate nets in the study area, for instance, is analogous to the surface form of modern permafrost fissures (Aartolahti, 1977). The average size of the Saginaw patterns (380 x 223 ft) is similar to those of ice-wedge polygons reported from elsewhere in North America and from northern Eurasia. As shown in Table 8, active and inactive tundra polygons average 34 to 767 feet in diameter, including both small features (7-10 ft in diameter) and very large examples (>3,000 ft across). Most of the fossil polygons discussed in the literature are smaller than the latter, with average diameters of 37-112 feet.

Table 8

Reported sizes of active, inactive and fossil tundra polygons

Location	Diameter (ft)	Reference
a) Active and Inactive Structures		
south of Barrow, Alaska	10–200	Hussey and Michelson, 1966
_____	164–656	Tricart, 1969
Vorkuta region, USSR	82–3,280	Dylik, 1966
Bolshezyemielskay tundra, USSR	10–3,280	Dylik, 1966
_____	10–100	Brown and Kupsch, 1974
near Barrow, Alaska		Black, 1952a
initial polygons	33–328	
secondary polygons	13–26	
tertiary polygons	3–10	
_____	10–328	Lachenbruch, 1966
_____	7–100	Péwé, 1966a
northern Sweden	33–131	Rapp and Clark, 1971
b) Fossil Structures		
southern Finland	7–43	Aartholati, 1970
northern Great Plains, USA	50–200	Clayton and Bailey, 1970
southern Sweden	115–213	Johnsson, 1963; 1981
Quebec, Canada	66–197	Lagarec, 1973
northern Norway	13–108	Svensson, 1964a
Jutland, Denmark	16–33	Svensson, 1972
northern Germany	7–49	Svensson, 1976
central New Jersey	10–100	Walters, 1975; 1978
west-central Indiana	50–100	Wayne, 1963
west-central Indiana	49–197	Wayne, 1967
central Iowa	4–20	Wilson, 1958
Lappland	33–131	Rapp and Rudberg, 1964
eastern England	7–35	Williams, 1964
northern Norway	131–213	Ohrengren, 1967
southern Alaska	7–98	Péwé, Church and Andreson, 1969
southern England	25–50	Gruhn and Bryan, 1969

However, large fossilized structures, approximately 200 feet in diameter, have been reported from the northern Great Plains, Indiana and Quebec, as well as from southern Sweden and northern Norway.

The relief-marking of the Saginaw patterned ground (low mesh, high center) is consistent with the hypothesis that it resulted from the thermal degradation of a network of ice wedges (Christensen, 1978; Washburn, 1978). This aspect of thermokarst modification of the patterns during their waning development will be discussed in more detail in a subsequent section.

On the basis of its structural and sedimentological characteristics, I interpret the soil wedge at the Bridgeport site to be an ice-wedge pseudomorph which documents the former existence of permafrost in the Saginaw Lowland. The medium-sand texture of its infilling material clearly shows that it could not have formed pedogenically from the surrounding sandy clay loam to clay loam till and the abrupt boundary between these two sediments suggests that the sand was deposited from above into a pre-existing wedge-shaped void in the drift. Although it lacks stratification, this sandy infill material is presumed to have been deposited by running water in a low-energy environment, augmented by eolian processes.

Evidence of pressure-effect deformation structures is lacking at the Bridgeport site, but this is undoubtedly the result of the massive, unstratified nature of the till. A similar situation was reported by Morgan (1982) for ice-wedge casts near Muir, Ontario. The relative paucity of pebbles and cobbles in the drift surrounding the Bridgeport wedge made it difficult to assess whether any realignment of elongated clasts existed. The long axis of one roller-shaped pebble in the till adjacent to the basal section of the pseudomorph was oriented parallel to the strike of the wedge cast, but another elongated clast not far away was oriented transverse to the wedge axis (Plate X).

The downward-tapering wedge form and near-vertical axis orientation of the Bridgeport wedge are both characteristic of true ice-wedge casts. No conclusive evidence of a relict permafrost table was observed in the study area, but palynological data from elsewhere in Michigan (to be discussed in a subsequent chapter) indicate that tundra conditions, and therefore possibly permafrost, were penecontemporaneous with the onset of pattern formation in the Saginaw Lowland.

The somewhat poorly drained loam and silt loam soils underlying most of the patterned ground in the study area would have been saturated with ice when they were perennially frozen during the Late Wisconsinan. Multiple wedge casts are lacking in the Saginaw valley, but the Bridgeport wedge is directly associated with a surficial nonsorted net. The overall paucity of fossilized ice-wedge casts in the study area is, nevertheless, in accordance with the textures of the host sediments which are prone to flowage upon thaw, an edaphic condition which greatly reduces the opportunity for ice-wedge replacement.

The large mesh dimensions (crack spacings) and irregular net form of the Saginaw patterned ground are indicative of permafrost cracking which was primarily controlled by randomly distributed flaws in the regolith. This type of cracking pattern is typical of recently drained areas of permafrost terrain (Lachenbruch, 1966) and is, therefore, consistent with the late-glacial drainage history of the study area. Oriented, orthogonal patterned ground, with one set of cracks parallel to a shoreline and a second set perpendicular to it, is often associated with slowly draining lakes on permafrost. With rapid shoreline recession, on the other hand, no such orientation would be expected (Lachenbruch, 1966). The short time

(scale = 15cm)

Plate X. Basal section of the Bridgeport wedge exposed in the ditch floor showing the orientation of two elongated pebbles.

duration for the lake level reduction from Warren I to Elkton is corroborated by the lack of oriented patterned ground in the Saginaw Lowland.

Based on the Late Wisconsinan chronology of the proglacial lakes in the study area, on the one hand, and the spatial agreement of some of their shorelines with the elevational limits of the patterned ground, on the other, I suggest that the formation of the nets occurred within a time span of 350 to 600 years (refer to discussion on p. 37). The large size of the nets in the Saginaw Lowland may be explained by this relatively short period available for their formation, since smaller patterns are usually the result of repetitive subdivisions of primary fissures during a protracted period of permafrost cracking (Dostovalov and Popov, 1966; Dylik, 1966). The width and depth of the ice-wedge cast at the Bridgeport site also suggest short-lived permafrost conditions. Black (1952b; 1974) determined that ice-wedges on the arctic coastal plain of Alaska were growing horizontally at the annual rate of 1-3mm/year and similar rates were measured by Mackay (1974) for ice-wedge cracks on Garry Island, Northwest Territories. Although these rates cannot be directly extrapolated to the Saginaw Lowland during the Late Wisconsinan, they nevertheless indicate that the ice wedge documented by the Bridgeport pseudomorph (ca. 15cm wide) could have formed in the 350 year interval between Warren I and Elkton. The dominant occurrence of the nonsorted nets on the finer-textured soils of the study area also suggests a relatively mild thermal regime in the permafrost (Dylik, 1966).

The spatial correlation between the Elkton shoreline and the lower elevational limit of patterning indicates that most of the nonsorted nets formed subaerially. Patterned ground, resulting from permafrost cracking, can form beneath shallow water as well and has been reported from various places (Mackay, 1967; Kerfoot, 1972; Danilov, 1973; Shilts and Dean, 1975).

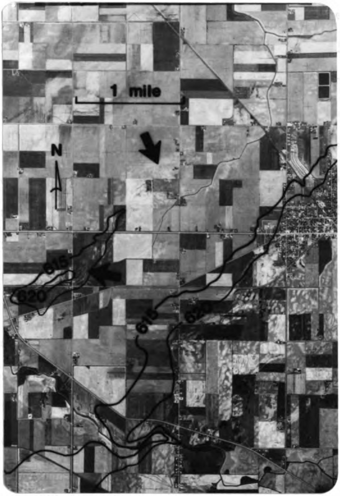
At several locations in the study area, faint patterned ground, which may have formed subaqueously, occurs at elevations slightly below the Elkton level on sites interpreted as spits or offshore bars formed in Lake Elkton (Plate XI). If these nonsorted nets did form underwater, the cracking must have initiated within subaqueous permafrost rather than at the lake-ice surface because the latter situation could not allow the recurrence of the identical geometric pattern from one year to the next (Mackay, Konischev and Popov, 1979).

Thermokarst Modification of the Saginaw Patterned Ground

The subtle morphology and sedimentological characteristics of the nonsorted nets throughout the Saginaw Lowland suggest that thermokarst erosion,[1] rather than ice-wedge replacement, was the dominant geomorphic process associated with the degradation of the permafrost in the study area. The morphologic importance of thermokarst in areas of perennially frozen ground has been emphasized by Kachurin (1962), Svensson (1970), Aleshinskaya, Bondarev and Gorbunov (1972) and Soloviev (1973).

Thermokarst develops in response to the disruption of the thermal equilibrium of permafrost by either climatic (e.g. increase in termperature, precipitation and/or continentality) or nonclimatic (e.g. forest fires, agricultural activities, construction, etc.) factors (Czudek and Demek, 1970). Because of the greater ice content in perennially frozen soils having impaired drainage, thermokarst is typically best developed in lowland environments. French (1974) attributed regional thermokarst to a climatic amelioration which furthurs a progressive lowering of the permafrost table; this appears to have been the case in the Saginaw

[1] Thermokarst is the process of melting ground ice accompanied by local collapse of the surface and the formation of depressions (Muller, 1947; Washburn, 1973; Brown and Kupsch, 1974).



(NASA-JSC 309-22-156; May 13, 1975; Original in color)

Plate XI. Conspicuous patterns confined to terrain above the Elkton beach (620 ft) near Reese, Michigan; faint nets (arrows) are associated with an Elkton offshore bar.

Lowland as proglacial Lake Elkton drained during the Late Wisconsinan.

The thawing of ice-wedge polygons within permafrost can produce circular or ovoid mounds[2] separated by curvilinear depressions which are situated over the melting ice wedges. This type of thermokarst topography develops in stages, as the active layer thickens (Schumskiy and Vtyurin, 1966; Czudek and Demek, 1970; Soloviev, 1973). In the initial phase (Figure 38a), high-centered polygons form as the reticulate network of ice veins begins to thaw. These trough-like depressions grow successively deeper as the thermal erosion of the wedge ice continues. The polygon cores usually retain their initial elevations and their flat tops until the encircling troughs reach a depth of about 1m (Figure 38b). This amount of local relief is generally sufficient to induce slumpage and/or flowage of the unstable active layer which tends to smooth-out the topography (Figure 38c). In addition, the melting of interstitial ice in the permafrost can obliterate the deformation structures frequently associated with ice-wedge development (Dylik, 1968).

According to French (1975), the amount of ground ice in saturated permafrost usually exceeds the liquid limit[3] of the regolith, making it prone to liquefaction upon thaw. This type of rapid gelifluction probably had a significant geomorphic impact on the landscape of the Saginaw Lowland as the climate ameliorated during the late Port Huron Stadial (early Twocreekan Interstadial ?). For example, the liquid limits of the parent materials of the four soil series commonly associated with the Saginaw

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[2]These inter-trough mounds are called baydjarakhs or cemetery mounds in Siberia (Brown, 1967) and thermokarst mounds in Alaska (Péwé, 1954).

[3]The liquid limit is the percent water content of unconsolidated material at the point where it passes from a plastic solid to a turbid liquid (American Geological Institute, 1962).

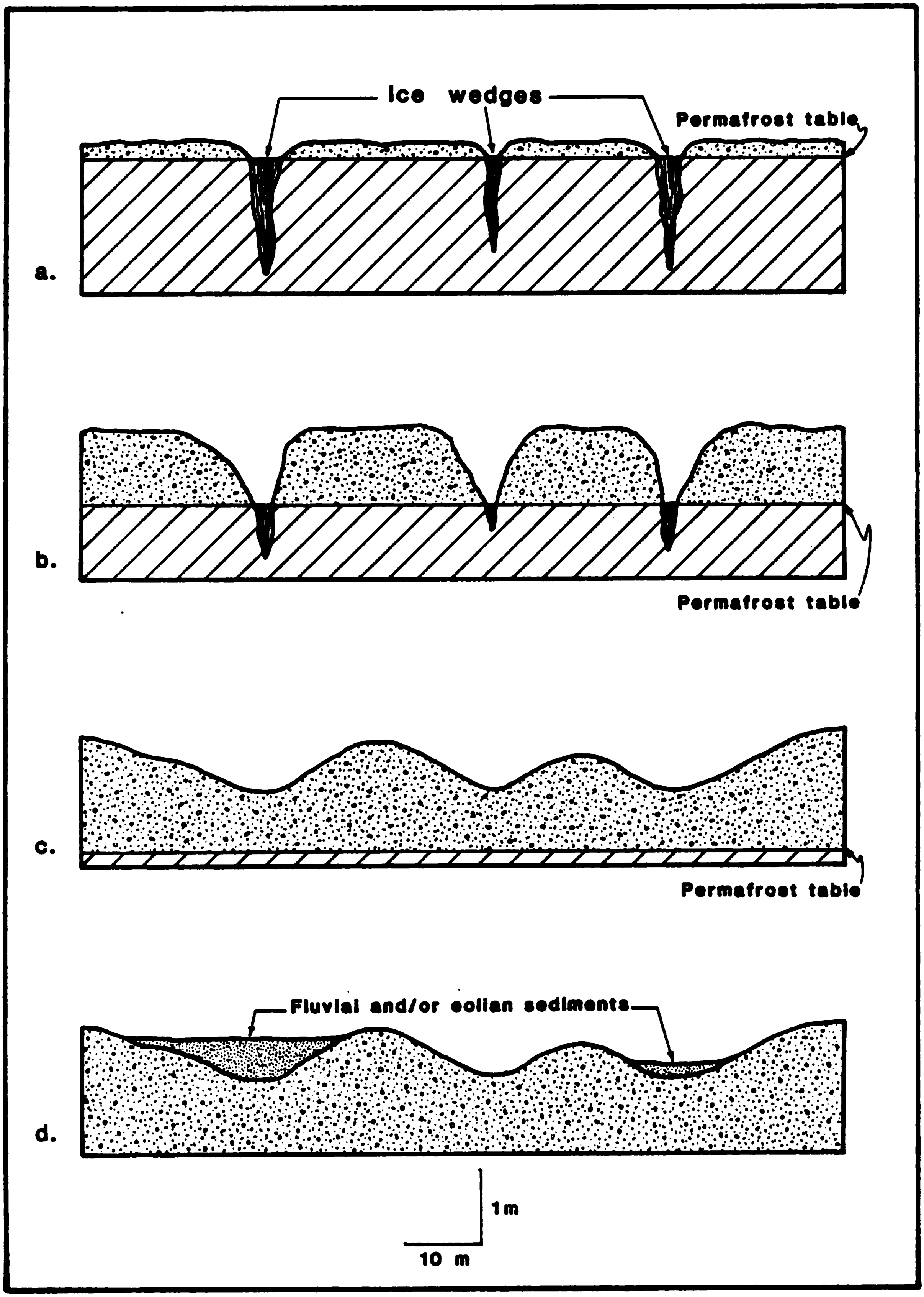

Figure 38. Suggested sequential development of thermokarst topography in the Saginaw Lowland.

patterned ground (Capac, Londo, Parkhill and Tappan) range from 15 to 35% (Soil Conservation Service, 1978a; 1978b; 1979a; 1979b). In comparison to these limits, Czudek and Demek (1970) reported that perennially frozen loam soils under saturated conditions can contain 30 to 80% segregated and/or vein ice. The pattern mesh in the study area was initially formed by thermal contraction cracking and ice-wedge development in perennially frozen ground, as revealed by the ice-wedge cast at the Bridgeport site. The final morphological expression of these features, in particular their reticulate rather than polygonal form, may be attributed to thermokarst processes operating in an ice-rich permafrost environment. As illustrated by the sedimentological data from the Lawndale site, the last development phase of the Saginaw patterned ground involved the localized infilling of some of these curvilinear thermokarst depressions with fluvial or eolian sediments (Figure 38d).

CHAPTER V

PALEOENVIRONMENTAL SIGNIFICANCE OF THE PATTERNED GROUND IN THE SAGINAW LOWLAND

Introduction

The concept of interpreting the morphology of the earth's surface in terms of past climatic events is one of the major historical underpinnings of geomorphology. Since the development of the Glacial Theory in the early part of the 19th century, it has been recognized that the formation, expansion and eventual disappearance of glaciers occurred in response to climatic change. Concurrent with the birth of this idea of an "ice age" were numerous observations by earth scientists of nonglacial evidence of former cold climates--remains of the woolly mammoth, fossil shells of cold-water snails, frost-riven bedrock, solifluction mantles and the like. These data were used, individually and collectively, to infer paleotemperatures colder than those prevailing today at particular locations. In this respect, periglacial geomorphology can make unique contributions to the study of the Quaternary because several periglacial landforms form only in areas underlain by permafrost, which have mean annual ground temperatures $\leq$ 0°C.

The distribution of permafrost in arctic and subarctic North America has changed very little since the end of Pleistocene time, but its distribution in the temperate latitudes underwent major dislocations during the late Quaternary (Péwé, 1973). Fossil biological evidence can suggest that more rigorous climatic conditions once existed in temperate North America, but it cannot document the former presence of permafrost. Other periglacial indicators, such as involutions, block accumulations, talus fields and asymmetrical valleys, are often best developed in permafrost areas, but they do not require perennially frozen ground to form. The past existence of permafrost can only be ascertained from fossil examples of ice and sand wedges and their associated patterned ground, pingos, rock glaciers and perhaps altiplanation terraces (Brown and Péwé, 1973; Péwé, 1973). French (1976) takes a more conservative view by stating that the only reliable indicators of former permafrost are the casts of ice or sand wedges.

Thermal contraction cracking is governed, to a major extent, by the temperature regime of the upper thirty feet or so of permafrost. While a temperature change of only 4°C is sufficient to initiate cracking in supersaturated perennially frozen ground, less saturated or thermally less conductive permafrost may require a flux of 8°-10°C to begin cracking (Black, 1976). Studies in Siberia have established that ground temperatures of only -2° to -4°C promoted ice wedge development in fine-grained materials, but temperatures of -7° to -8°C were necessary to maintain active ice wedges in gravel deposits (Romanovskij, 1973). The significant temperature decreases necessary for contraction cracking typically occur in areas of continuous permafrost with thin active layers and a temperature below -5°C at the depth of zero annual amplitude. The microclimate of local areas of discontinuous permafrost may also allow thermal contraction-cracking, but ice-wedge growth in such environments is slower and more aperiodic, compared to regions of continuous permafrost (Black, 1976). Ice wedges rarely form in sporadic permafrost. Ice wedge growth is typical in areas having minimum winter temperatures of less than -15° to -20°C at the permafrost table if the perennially frozen ground has the mechanical properties of polycrystalline ice (Lachenbruch, 1966; French, 1976). Péwé (1975) reported minimum winter ground temperatures at the permafrost table to be

<-11°C for actively growing ice wedges and between -4° and -10° or -15°C for inactive wedges in Alaska.

The relationship between mean annual air temperature (MAAT) and a thermal regime of the ground which promotes contraction cracking and ice wedge growth is complex. For example, average annual air temperatures can be 2° to 6°C cooler than mean annual ground temperatures (Gold and Lachenbruch, 1973; Péwé, 1975). Additionally, as Black (1976) has pointed out, thermal contraction-cracking is often controlled more by local surface conditions and short-lived cold spells than by annual temperature regimes.

Notwithstanding the difficulties involved in the quantification of the relationship between ice wedge growth and mean annual air temperature, several general observations can be made. On the basis of extensive research in Alaska, presently active ice wedges appear to be restricted to areas having MAAT of -6° to -8°C or colder (Péwé, 1964, 1966a, 1966b, 1975; Péwé, Church and Andresen, 1969; Washburn, 1973). Inactive ice wedges occur in areas of Alaska where the MAAT varies from -2° to -6° or -8°C. Gold and Lachenbruch (1973) concluded that the discontinuous permafrost region, where ice-wedge formation is frequently inactive, was bounded by the -1° and -6°C MAAT isotherms and that continuous permafrost (associated with active ice wedges) occurred in areas having MAAT of less than -6°C. Brown and Péwé (1973) cite the -4°C MAAT isotherm as the southerly limit of discontinuous permafrost and the -8.5°C MAAT isotherm as the southern boundary of continuous permafrost.

Paleoclimatic Implications of the Saginaw Patterned Ground

The nonsorted nets in the Saginaw Lowland are the result of permafrost cracking and ice-wedge development during a time span beginning about 12,730 years ago with the fall of proglacial meltwaters from the Warren I level and ending with the draining of Lake Elkton (not later than 12,400 yrs B.P.). This patterned ground documents a climate which was considerably colder and more rigorous than at present. The mean annual air temperature which may have prevailed during this period when ice wedges were actively growing in the study area can be deduced from the climatic conditions requisite for ice wedge formation today.

The mean annual air temperature in the Saginaw Bay area today is 8.3°C and the average minimum winter air temperature is -8.3°C (Michigan Weather Service, 1974). If the Saginaw patterned-ground complex formed in continuous permafrost, the MAAT may have been 14°-16°C colder than at present. Undoubtedly, this estimate represents the maximum temperature depression for this brief period (12,730-12,400 yrs B.P.). Considering the fine-textured soils on which most of the net cells occur and the width and depth of the ice-wedge cast at the Bridgeport site, it is more likely that the ice wedges in the Saginaw Lowland formed in discontinuous permafrost having an average ground temperature of -2° to -4°C. The MAAT may have been on the order of 9°-14°C colder than today (i.e., -1° to -6°C). As noted by Morgan (1982), katabatic winds flowing off the continental ice mass may have locally depressed temperatures in the periglacial zone, particularly near places where favorable ice-surface configurations concentrated such cold air drainage. During the Late Wisconsinan, the Saginaw Lowland may have been cooled by katabatic winds which were focused on the area as a result of the more rapid dissipation of the Saginaw Lobe compared to the neighboring ice lobes in the Michigan and Huron basins.

The occurrence of discontinuous permafrost which supported ice wedge growth in the Saginaw Lowland during the Late Wisconsinan indicates that precipitation, particularly snow, may have been much lower then than at present. Studies conducted over the last decade and a half at the McGill Sub-Arctic Research Laboratory, Schefferville, Quebec (approximate MAAT -5°C) have documented that snow cover is the most important single factor controlling the distribution of perennially frozen ground in this area of discontinuous permafrost (Gold and Lachenbruch, 1973; Nicholson and Granberg, 1973). Earlier studies indicated that snow depths greater than 40cm were sufficient to prevent permafrost formation (Annersten, 1966), but more recent investigations have revised this figure to 70-75cm (Nicholson and Granberg, 1973).

Geomorphic Evidence of Former Periglacial Conditions and Permafrost From Elsewhere in the Great Lakes Region

Fossil periglacial features have been reported from many places in the Great Lakes Region. For example, talus accumulations, block streams, block fields and asymmetrical valleys indicative of a former "frost climate" have been studied in the Driftless Area of southwestern Wisconsin (Smith, 1949, 1962; Judson and Andrews, 1955). Wayne (1967) investigated asymmetrical valleys in central and southern Indiana and attributed them to periglacial frost action. Involutions, possibly resulting from freeze-thaw activity in the active layer above permafrost, have been described from northeastern and north-central Illinois (Sharp, 1942; Ekblaw and Willman, 1955; Frey and Willman, 1958), central and southern Indiana (Wayne, 1956, 1963a; Gamble, 1958) and northwestern Ontario (Sutton, 1963). Leighton and Brophy (1961) interpreted enlarged bedrock joints south of Carbondale, Illinois to have resulted from periglacial frost action. Straw (1966) attributed the mass movement of dolomite blocks in the Niagaran Escarpment south of Meaford, Ontario to periglacial conditions associated with the Valders ice advance. In contrast to these areas, the scarcity of periglacial phenomena in Ohio has been noted by Goldthwait (1959). As mentioned previously, however, none of these fossil periglacial features are reliable indicators of former permafrost.

Péwé (1973) assumed that Wisconsinan permafrost formed in front of the expanding continental glaciers and persisted beneath the ice in selected areas where the bottom temperature was less than 0°C. Subglacial temperatures below freezing can occur in pressure melting situations (-2° to -1°C) or where the basal ice is frozen to the underlying ground. In areas south of the maximum extent of Wisconsinan ice, periglacial permafrost is thought to have formed 22,000 to 14,000 years ago or earlier (Péwé, 1973). As the ice margin withdrew to the north, recently uncovered drift became perennially frozen and, in those areas where especially rigorous conditions existed, ice wedges formed (Brown and Péwé, 1973).

Figure 39 shows the locations of all reported permafrost indicators in the Great Lakes Region which have been accepted by most researchers. Further documentation of these sites is given in Table 9. By far the greatest number of ice-wedge casts have been observed in Wisconsin (Black, 1965). The majority of these pseudomorphs occur along or south of the maximum extent of Wisconsinan ice (locations 1-19, Figure 39) and are thought to have formed 32,000 to 29,000 years ago during the late Altonian (locally termed Rockian).

The four ice-wedge casts in Columbia County, Wisconsin (location 20) are interpreted as having formed during the late Woodfordian 16,000-12,500 yrs B.P., but their location almost 50 miles beyond the local correlative of the Port Huron Moraine (ca 13,000 yrs B.P.) suggests their age is probably closer to the 16,000 yrs B.P. estimate. The two wedge casts at site 21 (Outagamie County, Wisconsin), on the other hand, are located several tens of miles proximally to the same Port Huron correlative moraine and

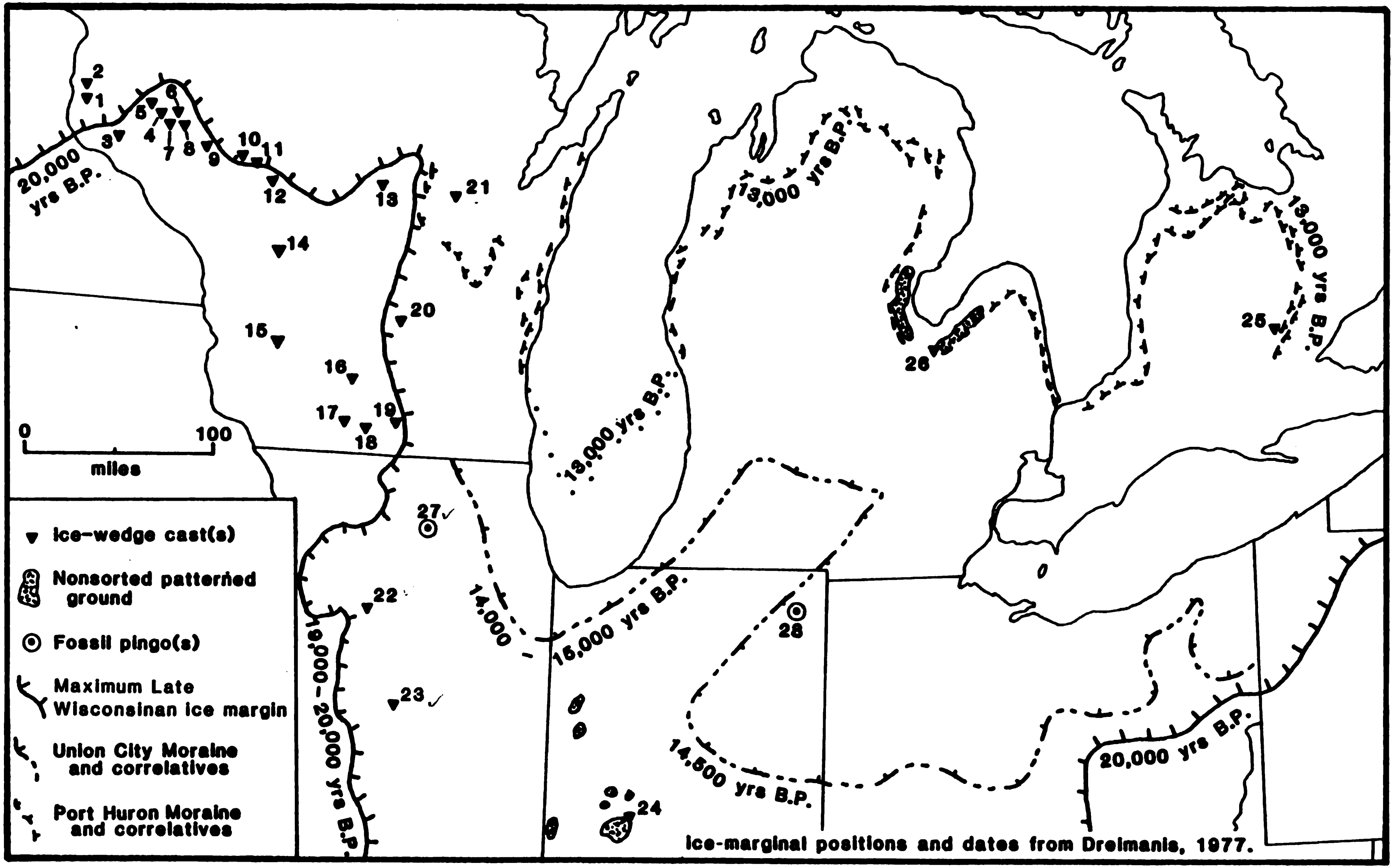

Figure 39. Geomorphic indicators of permafrost in the Great Lakes Region.

Table 9

Geomorphic indicators of former permafrost in the Great Lakes Region

Map Location Number	Reference	Locality	Feature(s)	Time of Formation (yrs B.P.)
1	Black, 1965	St. Croix Co., Wisconsin	30+ ice-wedge casts	32,000-29,000
2	Black, 1965	St. Croix Co., Wisconsin	6 ice-wedge casts	32,000-29,000
3	Black, 1965	Pierce Co., Wisconsin	3 ice-wedge casts	32,000-29,000
4	Black, 1965	Dunn Co., Wisconsin	1 ice-wedge cast	32,000-29,000
5	Black, 1965	Dunn Co., Wisconsin	1 ice-wedge cast	32,000-29,000
6	Black, 1965	Eau Claire Co., Wisconsin	17 ice-wedge casts	32,000-29,000
7	Black, 1965	Eau Claire Co., Wisconsin	several ice-wedge casts	32,000-29,000
8	Black, 1965	Eau Claire Co., Wisconsin	14 ice-wedge casts	32,000-29,000
9	Black, 1965	Eau Claire Co., Wisconsin	several ice-wedge casts	32,000-29,000
10	Black, 1965	Clark Co., Wisconsin	several ice-wedge casts	32,000-29,000
11	Black, 1965	Clark Co., Wisconsin	several ice-wedge casts	32,000-29,000
12	Black, 1965	Jackson Co., Wisconsin	3 ice-wedge casts	32,000-29,000
13	Black, 1965	Portage Co., Wisconsin	25+ ice-wedge casts	32,000-29,000
14	Black, 1965	Monroe Co., Wisconsin	26+ ice-wedge casts	32,000-29,000
15	Black, 1965	Richland Co., Wisconsin	2 ice-wedge casts	32,000-29,000
16	Black, 1965	Dane Co., Wisconsin	several ice-wedge casts	32,000-29,000
17	Black, 1965	Green Co., Wisconsin	1 ice-wedge cast	32,000-29,000
18	Black, 1965	Green Co., Wisconsin	4 ice-wedge casts	32,000-29,000
19	Black, 1965	Rock Co., Wisconsin	several ice-wedge casts	32,000-29,000

Table 9 (Cont'd)

Map Location Number	Reference	Locality	Feature(s)	Time of Formation (yrs B.P.)
20	Black, 1965	Columbia, Co., Wisconsin	4 ice-wedge casts	16,000–12,500
21	Black, 1965	Outagamie Co., Wisconsin	2 ice-wedge casts	16,000–12,500
22	Horberg, 1949	Bureau Co., Illinois	1 ice-wedge cast	14,000
23	Frey and Willman, 1958	Woodford Co., Illinois	1 ice-wedge cast	22,000
24	Wayne, 1967	Montgomery Co., Indiana	2 ice-wedge casts	18,000–17,000
		west-central Indiana	nonsorted patterned ground	21,000–17,000
25	Morgan, 1972	Kitchener, Ontario	1 ice-wedge cast	13,500–13,000
		Kitchener, Ontario	nonsorted patterned ground	13,500–13,000
	Morgan, 1982	Muir, Ontario	7 ice-wedge casts	15,000–13,000
		southwestern Ontario	nonsorted patterned ground	15,000–13,000
26	THIS STUDY	Saginaw Co., Michigan	1 ice-wedge cast	13,000–12,400
		Bay, Midland, Saginaw and Tuscola Co., Michigan	nonsorted nets	13,000–12,400
27	Flemal, Hinkley and Hesler, 1973	DeKalb, Illinois	500+ fossil pingos	18,000–17,000
28	Wayne, 1967	northeastern Indiana	1 possible fossil pingo (?)	<14,500

must have formed sometime later than 13,000 yrs B.P.

A single ice-wedge cast was reported from location 22 (Horberg, 1949) and also at site 23 (Frey and Willman, 1958), but in both cases the descriptive data provided in the literature are too meager to allow a proper assessment of their significance. Wayne (1967) discovered two ice-wedge casts in Montgomery County, Indiana (site 24) associated with nonsorted patterned ground which probably formed between 18,000 and 17,000 years ago.[1] He also reported isolated groups of patterned ground from several other locations in west-central Indiana which may have formed at about the same time.

Nonsorted patterned ground and associated ice-wedge pseudomorphs near Kitchener, Ontario (locality 25) were investigated by Morgan (1972) and Greenhouse and Morgan (1977) who concluded that they resulted from thermal contraction cracking of permafrost and suggested a Late Wisconsinan MAAT 13°-14°C colder than at present. Because these features were located distal to the Paris Moraine (a Port Huron Moraine correlative) on Port Stanley Till, Morgan (1972) assigned them an age of 13,500-13,000 yrs B.P. However, a reinterpretation of glacial Lake Whittlesey shoreline data from southwestern Ontario (Barnett, 1979) suggests that the Paris Moraine (and, therefore, the Kitchener patterned ground) may be of Port Bruce Stadial age (14,500-13,500 yrs B.P.). More recently, Morgan (1982) reported numerous other occurrences of patterned ground in southwestern Ontario and described

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[1]In two previous review articles (Brown and Péwé, 1973; Péwé, 1973) these ice-wedge casts were erroneously listed as younger than 14,500 yrs B.P. Wayne never included a date for these features in his published descriptions, but the pseudomorphs occurred in the Cartersburg Till Member of the Trafalgar Formation which is younger than the underlying *Vertigo alpestris oughtoni* bed, the average age of which is 20,083 ± 831 yrs B.P. (Wayne, 1963b). The wedge casts are located on the distal flank of the inner Crawfordsville Moraine, a possible correlative of the Farmersville and Reesville Moraines farther to the east which formed about 17,000 years ago (Wayne, 1965; Dreimanis and Goldthwait, 1973).

several ice-wedge casts which were excavated near Muir, Ontario. Considering the rock-stratigraphic units underlying these polygons, it was concluded that the patterns formed in the period from about 15,000 to 13,000 yrs B.P. Morgan suggested that these features indicated a MAAT of -3°C to -4°C, at this time.

More than 500 fossil pingos occur in an area of approximately 115 square miles (site 27) near DeKalb, Illinois (Flemal, Hinkley and Hesler, 1973). Since modern pingos develop only in areas of permafrost, pingo scars are indisputable evidence of former perennially frozen ground (Flemal, 1976). These "DeKalb Mounds" were presumed to have formed 16,500-15,000 yrs B.P. on the basis of their stratigraphic position between the underlying Tiskilwa Till and the overlying Richland Loess, but more recent estimates place this time interval at 18,000-17,000 yrs B.P. (Dreimanis, 1977). Another circular soil feature, also interpreted as a pingo scar, was reported from near Corunna, Indiana in the northeastern part of the state (Wayne, 1967). This feature (location 28) was identified from aerial photographs but never investigated in the field. Without further substantiating field evidence, the pingo origin of this feature remains speculative.

On the basis of high quality acoustic profiling records, Bowlby (1975) reported an extensive network of fossil ice-wedge casts on the floor of the Kingston Basin of eastern Lake Ontario beneath almost 100 feet of water. Nearly 500 presumed pseudomorphs were detected in an area of about 0.6 mi^2 and were assigned an age of about 11,000 yrs B.P. Although an ice wedge origin for these patterns is within the realm of possibility, given the difficulty of correctly identifying true ice-wedge casts by normal visual observations and field sampling (Johnsson, 1959;

Black, 1976), such a genesis for these underwater features is questionable when based solely on acoustic data.

Palynological Evidence of Late Wisconsinan Tundra Environments in Michigan

After decades of research, a detailed paleobotanical record of late Pleistocene vegetation has been compiled in Europe. From the outset in the late 1940's, palynologists in this country anticipated that their studies would yield pollen spectra similar to those of their European colleagues, including a basal herb assemblage (particularly grasses, sedges and composites) representing late-glacial tundra conditions, overlain by several arboreal pollen zones indicative of postglacial vegetational succession. In this respect, the early pollen diagrams from the Midwest (e.g. Potzger, 1946, 1948, 1951) were disappointing; the basal organic sediments were usually dominated by *Picea* pollen, contained high percentages of *Pinus* pollen and oftentimes displayed significant amounts of pollen from thermophilous species such as *Quercus*. Unfortunately, most of these early pollen counts did not include herbaceous species, making it impossible to identify any of the common nonarboreal tundra indicators. In fact, Potzger's exclusion of nonarboreal pollen was vigorously criticized by Deevey (1951) who contended that evidence of the tundra zone was to be found in the underlying mineral sediments directly beneath the lowermost organic deposits. It is now recognized that many of these lacustrine and bog sample sites may not have become depositional basins until as much as one or two millenia after deglaciation as a consequence of the persistence of buried stagnant ice (Florin and Wright, 1969; Wright, 1971; Odgen, 1977).

Meager evidence of open tree stands, possibly representing park tundra, is available, however. The pollen record from George Reserve in Livingston County, for instance, although dominated by *Picea* at its base, included

30-35% herb pollen (Andersen, 1954). No radiocarbon dates were determined from this core, but the basal sediments were correlated with the Port Huron advance (13,000 yrs B.P.). Stoutamire and Benninghoff (1964) analyzed the organic detritus associated with a mastadon skull found at Pontiac, Michigan which was dated at 11,900 ± 350 yrs B.P. This material was dominated by Picea pollen (82.8% of total AP), but also contained large amounts of nonarboreal pollen (85% of total AP). Although such a high proportion of NAP can be indicative of incomplete forest cover, in this case more than half of the nonarboreal species were representative of shallow ponds, marshes or shrub swamps.

The best palynological evidence of Late Wisconsinan tundra conditions in Michigan comes from two widely separated but time-stratigraphically penecontemporaneous sites (Cheboygan and Lapeer counties). The well known Cheboygan bryophyte bed, of such importance as an interstadial marker, yielded the first solid data indicating tundra conditions in the state. This one-centimeter-thick moss layer occurred at a depth of just over four meters beneath red, clayey till capped by stratified sand and gravel. Four radiocarbon dates, ranging from 12,500 to 13,300 yrs B.P., were determined from the organic materials (Farrand, Zahner and Benninghoff, 1969), but according to Dreimanis and Goldthwait (1973) the most reliable of these dates, as a result of an alkali-acid pretreatment, is 13,300 ± 400 yrs B.P. (L-1064).

The pollen diagram shown in Figure 40 is based on the analysis of four samples: one from within the bryophyte bed, one from the subjacent sand and two from the overlying silty clay (Miller and Benninghoff, 1969). Of particular interest is the large amount of herb and shrub pollen identified in these samples. Cyperacea yielded the most abundant nonarboreal pollen, varying from 85% in the sand beneath the moss layer to 38% in the overlying

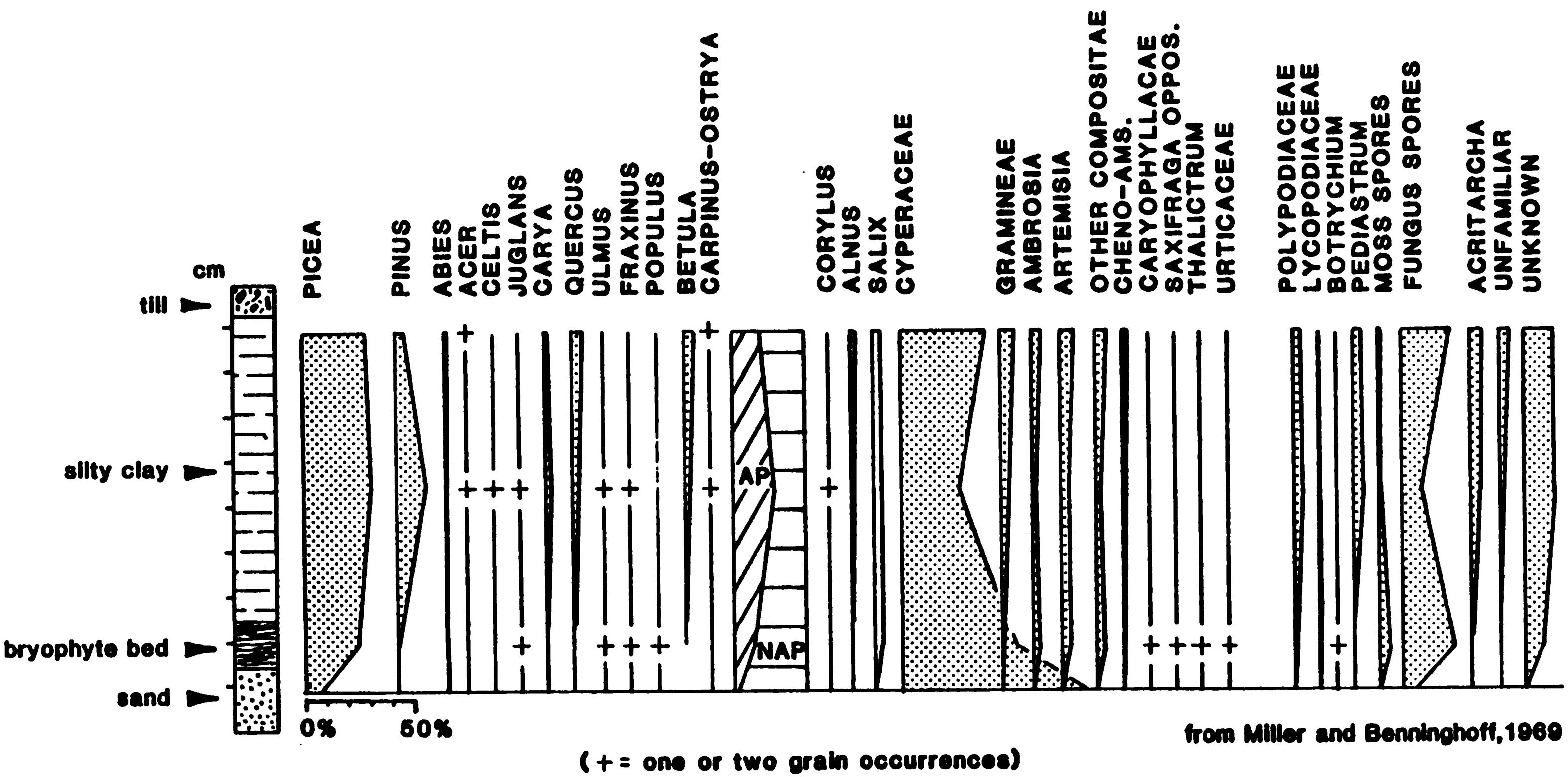

Figure 40. Pollen diagram of the Cheboygan bryophyte bed and associated sediments.

lacustrine sediments. Smaller, but still significant amounts of Alnus, Salix, Gramineae, Ambrosia and Artemesia were also detected. Of the arboreal pollen, Picea was the most common, ranging from 8% in the lowermost sample to 31% in the silty clay 3.5cm above the bryophyte bed. Pinus pollen accounted for less than 1% of the total AP in the organic zone and underlying sand and reached a maximum of only 13% in the younger lacustrine material. Betula pollen occurred only in the upper two samples and a small percentage of Abies pollen was detected in the three non-organic sediments, but not in the bryophyte bed.

In common with most late-glacial pollen spectra from Michigan, small amounts of pollen from thermophilous deciduous trees, such as Carya and Quercus, were identified in the upper three samples. Additionally, one or two grains of Acer, Celtis, Fraxinus, Juglans, Populus, Ulmus or Carpinus-Ostrya occurred sporadically throughout the samples. This pollen from more temperate arboreal vegetation may have been redeposited from older sediments, but more likely was transported to the site from great distances (Miller and Benninghoff, 1969).[2]

In addition to pollen, macroscopic plant fossils were preserved in the bryophyte bed; they consisted mainly of mosses, mixed with a few liverworts and some leaves, twigs and seeds of several vascular plants. Eight different species of mosses were identified, including Bryum cryophilum which is considered to be a truly arctic species (Steere, 1947). Macrofossils of six vascular plant species were recognized and among the three sedges classified was Carex supina, which is presently restricted to the Arctic and Subarctic.

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[2]Modern long-distance transport of pollen has been documented by Ritchie and Litchi-Federovich (1967) who identified small amounts of Carya, Fraxinus, Juglans, Quercus and Ulmus in the pollen rain at Churchill, Manitoba which is nearly 400 miles beyond the range of these genera.

The most abundant flowering plant in the bryophyte bed was Dryas integrifolia. According to Porsild (1957), this dwarf shrub is a ubiquitous pioneer species in the arctic or alpine tundra. The fossil remains of two other arctic-alpine indicator plants also occurred in the organic zone. Twigs and well-preserved leaves of Salix herbacea were identified, as well as fossil leaves of Vacinium uliginosum var. alpinum.

Both the pollen spectra and the macrofossil assemblage document open vegetation which was dominated by sedges and other herbaceous plants. Spruce and possibly other trees were locally present, but scattered, as indicated by the presence of the several tundra heliophytes, including Dryas integrifolia. The lack of a closed forest is also suggested by the relatively small total amount of spruce pollen in the spectra. An additional indicator of open tundra conditions is the larger-than-unity NAP/AP ratio in the bryophyte bed and in two other samples (Livingstone, 1955).

As pointed out by Miller and Benninghoff (1969), it is highly improbable that the many fragile structures (leaves, seeds, etc.) which were preserved in the organic debris could have been transported any significant distance and still remain identifiable. Thus, these macrofossils provide conclusive evidence that the plants which produced them were growing on or near the depositional site. Similar conclusions cannot be drawn from the pollen record, however, since both local and distant vegetation contribute to the pollen rain at any site. Taken together, the pollen spectra and macrofossil assemblage in the Cheboygan bryophyte bed document the existence of an open vegetation community at this northern Michigan site some 13,000 years ago which was floristically similar to present-day tundra communities in arctic or subarctic North America.

Additional evidence of late-glacial tundra conditions in Michigan comes from the Weaver Drain site in northeastern Lapeer County (Burgis, 1970; Eschman, 1978). This drainageway, located in a linear depression between two moraines, formed part of the Imlay Outlet of glacial Lake Maumee. Organic remains recovered from this locale yielded a radiometric age of 13,770 ± 210 yrs B.P. (I-4899).[3] Although the Weaver Drain material was not subjected to pollen analysis, the fragile macrofossils clearly document in situ tundra vegetation in the southeastern part of the state during the Mackinaw Interstadial. Paleoentomological data from the Weaver Drain site also indicate tundra-like conditions, although the presence of one fossilized bark beetle (Polygraphic rufipennis) suggests that trees were not far away (Morgan, Elias and Morgan, 1981). According to Morgan (1982), these data document an MAAT in the -1° to -4°C range.

Regional Synopsis of Late Wisconsin Tundra and Permafrost Indicators

The temporal and spatial inter-relationships between the paleobotanical tundra indicators and the previously discussed geomorphic evidence for periglacial permafrost are summarized in Figure 41. Among the oldest features shown are the DeKalb Mounds located proximally to the Bloomington Moraine on the Tiskilwa Till. According to Frey and Willman (1973), the most significant Woodfordian glacial retreat of the Lake Michigan lobe occurred between the deposition of the Tiskilwa and Malden Till Members of the Wedron Formation. Because no organic deposits have ever been found between these two tills, Dreimanis (1977) suggested that this phase of the ice retreat approximately 17,500 years ago may have represented a cold, dry episode rather than one of warming. The pingo origin for the DeKalb Mounds would be in agreement with this hypothesis.

[3]This deposit has been overlooked by even the most recent reviews of Michigan's late-glacial flora (e.g. Kapp, 1977), yet it contained well-preserved macrofossils of Dryas integrifolia, Salix herbacea and Vaccinium uliginosum.

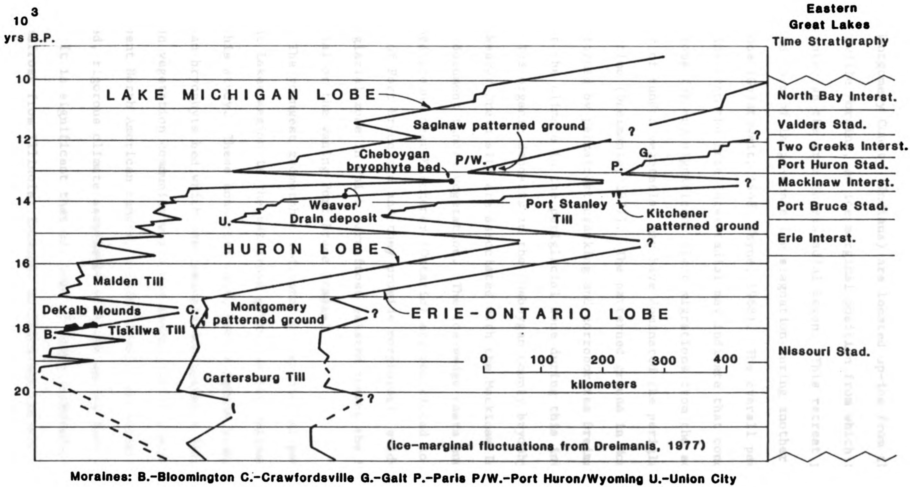

Figure 41. Time-distance diagram of ice-marginal fluctuations along the axes of the three major glacial lobes in the Great Lakes Region, showing the relationships between the paleobotanical evidence of tundra and the geomorphic indicators of Late Wisconsinan permafrost.

The contemporaneous patterned ground and associated ice-wedge casts in Montgomery County (Indiana) are located up-ice from the outer Crawfordsville Moraine, an ice marginal position from which the Huron lobe retreated as the Erie Interstadial began. This retreat probably occurred in the form of large-scale ice stagnation during another cold but dry episode (Goldthwait, 1968; Wayne, 1968). The overall paucity of organic remains from the Erie Interstadial may indicate that conditions were too rigorous for any significant plant migrations from the south and a thin cover of tundra vegetation may have dominated the periglacial zone at this time (Dreimanis, 1977). The patterned ground in Montgomery County was formed by permafrost cracking and corroborates Dreimanis' conclusions about the climate in the periglacial zone during this interval.

The organic deposits in the Cheboygan County bryophyte bed and at the Weaver Drain site are associated with the Mackinaw Interstadial and both document tundra vegetation. The ice-wedge casts and nonsorted patterned ground near Kitchener (Ontario) are restricted to the Port Stanley Till of Port Bruce age and they provide morphologic evidence of a cold periglacial zone in which permafrost existed during the Mackinaw Interstadial or the waning Port Bruce Stadial.

The youngest geomorphic indicator of periglacial permafrost in the Great Lakes Region is the patterned ground in the Saginaw Lowland described in this study. These nonsorted nets, only slightly younger than the Cheboygan bryophyte bed which conclusively documented a local Late Wisconsinan vegetation community which was floristically similar to those of the present North American tundra, provide fossilized evidence of a short-lived, rigorous climate associated with the waning Port Huron Stadial.

It is significant that all four of these geomorphic indicators of permafrost from Illinois, Indiana, Michigan and Ontario are associated with waning ice margins. Taken together, they indicate that at least localized areas of periglacial permafrost existed along the margins of the retreating Lake Michigan, Huron and Ontario lobes during the Late Wisconsinan.

Summary and Conclusions

As a result of interpreting numerous aerial photographs of varying scales, film type and date of acquisition, the true extent of patterned ground in Michigan's Saginaw Lowland has been delimited in this study. More than 350 mi^2 of patterned terrain occurs within a 3-8 mile-wide arcuate tract across parts of Arenac, Bay, Gladwin, Midland, Saginaw and Tuscola counties. These patterns consist of a reticulated network of broad, shallow troughs which encircle slightly higher centers. Individual pattern cells are typically oval in plan view, as indicated by the 1.7:1 average ratio of their major to minor axis lengths. They range in size from small, circular forms 79 feet in diameter to very large, elongated features measuring 1,289 x 480 feet. The average cell mesh is 380 x 223 feet across. On the basis of their geometry and relief marking, they are classified as nonsorted nets.

Morphostratigraphically, the Saginaw patterns occur upon, distal to and proximal from the Port Huron Moraine, the boundaries of which were reinterpreted during this research. It has been shown, for instance, that the extent of the Port Huron Moraine, particularly in Midland County, is greater than depicted on a map of the surface formations of the Lower Peninsula (Martin, 1955). Additionally, the waterlain portions of this ice-marginal feature have been more accurately delimited compared to previous interpretations.

On the basis of their juxtaposed boundaries, Tillema (1972) correlated the lower elevational limit of the Saginaw patterned ground with the level of glacial Lake Elkton. This relationship held true along the entire length (10-15 miles) of his study area in southwestern Bay County and north-central Saginaw County which is south of the Elkton zero-isobase. In order to assess the validity of this hypothesis, all proglacial lake shorelines in the study area, from the Warren I elevation down to the Elkton level, were mapped. For more than 100 miles, from the northern border of Bay County around to the Huron-Tuscola county line, the lower limit of the nonsorted nets corresponds remarkably well with the Elkton shoreline. Significantly, this correlation continues across the deformed zone north of the zero isobase and indicates that active pattern formation was contemporaneous with and bounded by Lake Elkton. Recent investigations from elsewhere in the Great Lakes basin (see Table 4, p. 45), have concluded that Early Lake Algonquin, the first stable water plane after Lake Elkton drained, formed by 12,400 yrs B.P. This represents the minimum date for the cessation of patterned ground formation in the study area.

The upper elevational limit of the nonsorted nets is more difficult to interpret, but appears to be related to the highest level of proglacial Lake Warren. A single radiocarbon date on wood samples from western New York established an age of 12,730 $\pm$ 230 yrs B.P. for this lake stage (Calkin, 1970). On the basis of their morphostratigraphic position alone, the patterns must be younger than 13,000 yrs B.P. (the age of the Port Huron Moraine and proglacial Lake Saginaw).

Although the Saginaw nets are topographically bounded by the Warren and Elkton shorelines, other landscape factors influenced their local distribution. Most of the reticulate patterns in the Saginaw Lowland formed in somewhat poorly drained loam or silt loam materials on surfaces with less than 3% slope and only 10-15 ft/mi^2 local relief.

Of the 14 proposed origins for nonsorted nets which were reviewed, only permafrost cracking and ice wedge development is supported by the data from the study area. The geometry and morphometry of the Saginaw patterns are very similar to known active, inactive and/or fossil tundra polygons from numerous locations. The structural and sedimentological attributes of the Bridgeport wedge clearly document that it is a true ice-wedge cast. As illustrated by the edaphic conditions at the Lawndale site, however, thermokarst erosion, rather than ice-wedge fossilization, was one of the more important geomorphic processes associated with the thawing of the permafrost in the Saginaw Lowland.

Studies from Alaska and elsewhere indicate that presently active ice-wedge formation is rare above certain threshold temperatures. Based on these relationships, the patterned ground in the study area, which formed by thermal contraction-cracking of permafrost, documents a brief interval within the Late Wisconsinan Substage (12,730-12,400 yrs B.P.) when the MAAT was on the order of -1° to -6°C, i.e., 9°-14°C colder than at present. In addition, the existence of this perennially frozen ground suggests that diminished winter precipitation and/or enhanced eolian activity prevailed in east-central Michigan at this time since snow depths greater than 50-75cm are known to prevent permafrost formation (Nicholson and Granberg, 1973).

Finally, the nonsorted nets in the Saginaw Lowland are the youngest of the four Late Wisconsinan permafrost indicators from Illinois, Indiana, Michigan and Ontario. All of these periglacial landforms are associated with waning glacial stadials. Taken together, they indicate that at least localized zones of rigorous climate existed during ice-marginal recessions and they suggest that some interstadial periods during the Late

Wisconsinan may have been initiated by cold, dry conditions rather than by warming.

Recommendations for Further Research

A largely qualitative approach has been taken in this study to describe the characteristics of the patterned ground in the Saginaw Lowland and its relationships to other environmental factors. Future research should concentrate on quantitative evaluations of these data. The comparisons of the spatial distribution of the nonsorted nets with respect to soil texture and drainage, local relief and elevation were based on interpretations of small-scale maps. By necessity, the topographic and edaphic details of the landscape in these graphic presentations had to be generalized. The specific correlation between patterned ground occurrences and soil management groups, for instance, is a problem which requires further investigation. Using appropriate sampling techniques, data could be generated and statistically analyzed so that confidence limits could be assigned to the co-occurrence of the nets by soil texture/drainage classes. A potentially more powerful analytical technique would be to quantitatively test the hypothesis that patterned ground in the study area is restricted to low-relief (i.e., $\leq$15 ft/mi^2) sites between the Elkton and Warren shorelines which are underlain by somewhat poorly drained loam and silt loam drift. Such a multivariate analysis would undoubtedly enhance our understanding of the environmental conditions optimal for the formation and/or fossilization of the Saginaw patterns and, at the same time, provide a more objective data base for the evaluation of other hypotheses which may be proposed in the future concerning the genesis of these features.

As mentioned earlier, the deformation structures which are common in the host sediment adjacent to ice-wedge casts were lacking at the Bridgeport site, probably because the till is massive and unstratified. Nevertheless, compressional forces must have been exerted on this material during the growth-cycle of the Bridgeport wedge when the saturated permafrost below the active layer and above the level of zero annual amplitude expanded as it warmed somewhat in the summer months. Evidence of these stresses may be preserved as a micro-fabric in the host material at the Bridgeport site and may be obvious in thin-sections cut from samples extracted from near the wedge perimeter after being impregnated with a plastic resin.

Another potentially valuable technique would be to measure the linear coefficient of thermal expansion of soil samples taken from the C horizons of various soil management groups in the study area. In the laboratory, samples of the same soil type but differing saturation levels could be tested in order to model the impact of soil water on thermal contraction. Data from such experiments could provide quantitative information by which the thermal contraction-crack origin of the Saginaw patterns could be evaluated.

The existence of permafrost in the Saginaw Lowland during the interval between 12,730 and 12,400 yrs B.P. presents the obvious challenge to search for evidence of contemporaneous perennially frozen ground elsewhere in Michigan. As a guide, the terrain between the Warren I shoreline and the level of Lake Elkton in other parts of the state should be given special scrutiny. A cursory perusal of published soil surveys and selected aerial photographs has revealed that numerous patches of patterned ground, similar in form and marking to the Saginaw nonsorted nets but of less extent, occur in parts of Monroe, Wayne, Macomb and St. Clair counties. Previous work by the author in Sanilac County concluded that the patterned ground in that vicinity may not be related to permafrost, but the impact of severe thermokarst erosion was not considered and this area should be re-examined with this hypothesis in mind.

The edaphic characteristics of the nonsorted nets in the Saginaw Lowland suggest that well-developed patterned ground in Michigan may be restricted to the somewhat poorly drained, finer-textured soils which are typical of the lake bed areas. However, small, scattered patches of patterned ground have been observed on airphotos of Branch, Hillsdale, St. Joseph, Cass and Calhoun counties where coarse-textured drift is common. These features need to be examined in terms of their morphometric, topographic, pedologic and stratigraphic characteristics in order to discern similarities and differences compared to the Saginaw Lowland patterns investigated in this study.

It appears that periglacial permafrost, as documented by fossil patterned ground, may have been more extensive in Michigan than was previously thought possible. Undoubtedly, this perennially frozen ground was discontinuous and probably formed only in relatively restricted areas where local conditions provided a conducive environment. Nevertheless, its impact on the sculpturing of the modern landscape has yet to be fully understood and awaits further research.

APPENDICES

APPENDIX A

SOIL MANAGEMENT GROUPS

The basic mapping unit shown on soil surveys is the soil series which is named for the town or other geographic feature nearest to the place where it was first recognized. Soils within a given series are similar to one another in their depth, thickness and arrangement of horizons and other biological, chemical and physical properties, but the series name indicates none of these characteristics. According to Mokma (1978), two of the most significant physical parameters of soils are their dominant profile texture and natural drainage conditions. Associations of soils based on these two factors are called Soil Management Groups and are denoted by the systematic arrangement of numbers and letters listed below.

A. Mineral soils developed from uniform parent material

Dominant profile texture	Symbol
>60% clay	0
40–60% clay	1
Clay loam and silty clay loam	1.5
Loam and silt loam	2.5
Sandy loam	3
Loamy sand	4
Sand (strong subsoil development)	5.0
Sand (medium subsoil development)	5.3
Sand (weak or no subsoil development)	5.7
Gravelly or stony loamy sand to loam	G
Bedrock at less than 20" depth	R

Dominant profile texture	Symbol
Alluvial or lowland soils	L
loamy	L-2
sandy	L-4

B. Mineral soils developed from parent materials of contrasting, juxtaposed textures

Dominant profile texture	Symbol
Clay, 20-40 inches, over gravelly sand	1/5
Sandy loam, 14-40 inches, over clay	3/1
Sandy loam, 20-40 inches, over loam to clay loam	3/2
Sandy loam, 20-40 inches, over gravelly sand	3/5
Loamy sand, 14-40 inches, over clay	4/1
Sand to loamy sand, 20-40 inches, over loam to clay loam	4/2
Sandy to loamy sand, 40-60 inches, over loam to clay	5/2
Loam, 20-40 inches, over bedrock	2/R
Sandy loam, 20-40 inches, over bedrock	3/R
Sand to loamy sand, 20-40 inches, over bedrock	4/R

C. Organic soils

Depth of organic material	Underlying material	Symbol
>51 inches		Mc
16-51 inches	Clay	M/1c
16-51 inches	Sandy loam to clay loam	M/3c
16-51 inches	Loamy sand to sand	M/4c
16-51 inches	Marl	M/mc
16-51 inches	Bedrock	M/Rc

Natural drainage is indicated by lower case letters:

a - well and moderatley well-drained

b - somewhat poorly drained

c - poorly and very poorly drained

APPENDIX B

ELECTRICAL RESISTIVITY SURVEYING

A schematic diagram of the apparatus used for electrical resistivity measurements is shown in Figure B1. In operation, an electrical current of about 100 vdc is passed through the soil body between the two end (current) electrodes while the voltage differences between the middle two (potential) probes is measured. Apparent resistivity is proportional to the ratio of voltage change across the potential electrodes to the total current.

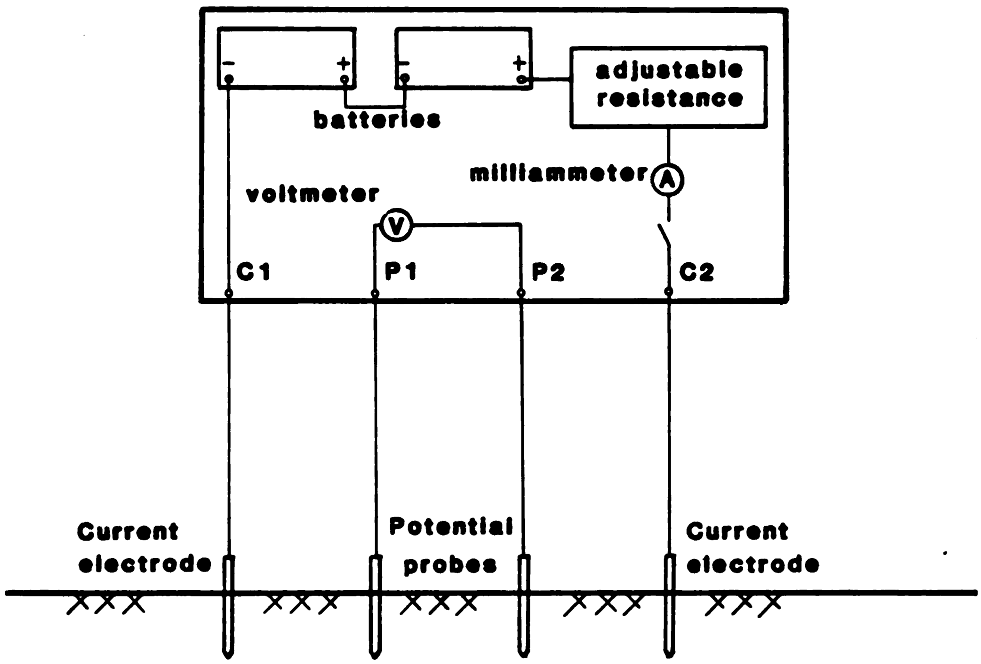

Figure B1. Schematic diagram of electrical resistivity apparatus.

A large variety of electrode configurations have been proposed for resistivity surveying, but the linear arrays are the most common. Figure B2 shows three of the frequently used linear arrays. The Lee and the

Wenner configurations, which are symmetrically arranged, are similar to one another with the exception of the additional potential probe in the middle of the Lee array. In both cases, however, the entire arrangement is moved laterally in fixed increments, but the Wenner array, having fewer electrodes, is less cumbersome in this respect. In the Schlumberger array configuration, on the other hand, the closely spaced potential probes are moved as a pair between the widely separated stationary current electrodes.

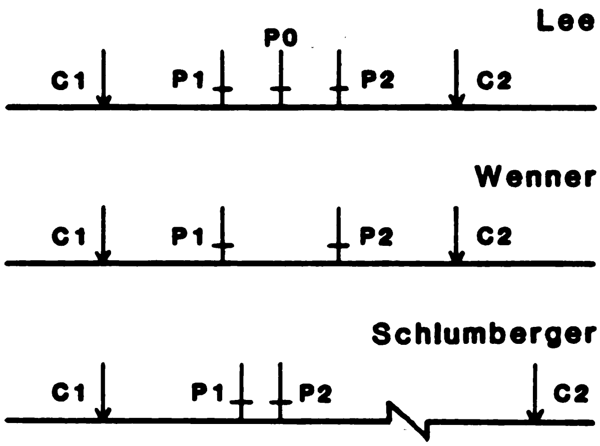

Figure B2. Linear electrode configurations commonly used in resistivity surveying.

The penetration depth of a resistivity profile is primarily determined by the distance between the current electrodes. According to Paransis (1973), less than 30% of the total current penetrates below a depth equal to the array length. The large separation distance between the current electrodes in the Schlumberger array, for instance, makes this configuration inappropriate for detecting shallow resistivity anomalies.

Figure B3 illustrates how near-surface resistivity anomalies can be detected using this instrumentation. According to Jakosky (1950), equipotential lines are displaced away from a zone of high conductivity and as

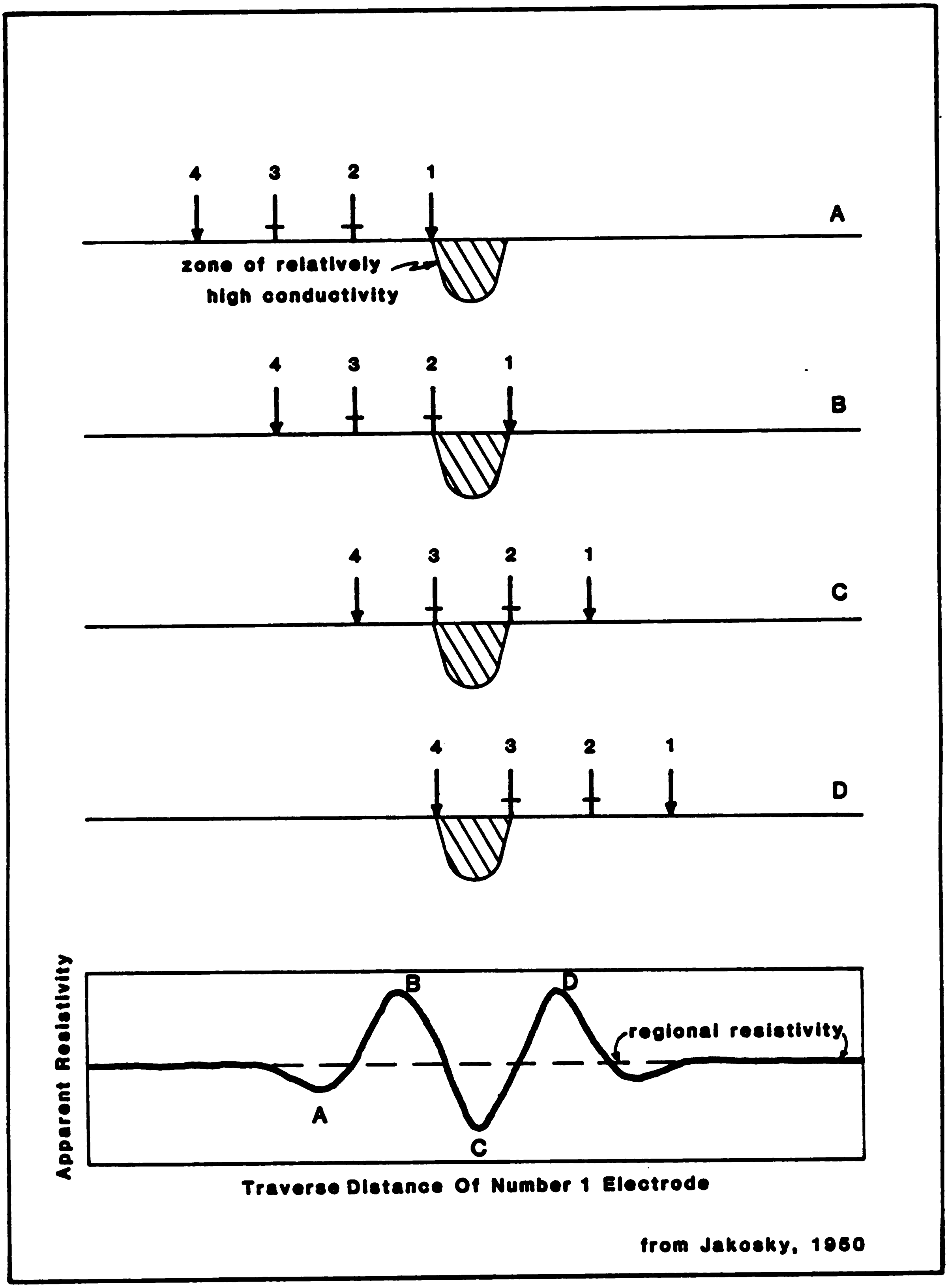

Figure B3. Detection of a near-surface resistivity anomaly.

the electrode array approaches such a conductor, the potential difference between probes 2 and 3 is decreased somewhat causing a slight lowering of the apparent resistivity at sample point A. At station B, the electrical current is short-circuited between electrodes 1 and 2 by the conductive zone, making the potential between probes 2 and 3 large and producing a maximum apparent resistivity value.

The opposite situation occurs at array location C. Here the potential difference, as measured across the conductor, is very small and apparent resistivity falls to a minimum. The relative electrode positions at station D are the same as were encountered at B and apparent resistivity once again is maximum. A Wenner array configuration passing over a zone of relatively low conductivity would produce an inverted resistivity curve having the same general characteristics.

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