Characterization and Mapping of Patterned Ground in the Saginaw Lowlands, Michigan: Possible Evidence for Late-Wisconsin Permafrost

David P. Lusch,* Kristy E. Stanley,† Randall J. Schaetzl,* Anthony D. Kendall,‡ Remke L. Van Dam,‡ Asger Nielsen,§ Bradley E. Blumer,* Trevor C. Hobbs,* Jonathan K. Archer,* Jennifer L. F. Holmstadt,* and Christopher L. May‡

**Department of Geography, Michigan State University*
†Department of Geography, University of Wisconsin–Madison
‡Department of Geological Sciences, Michigan State University
§Department of Geography and Geology, University of Copenhagen

We identified, mapped, and characterized a widespread area (>1,020 km^2) of patterned ground in the Saginaw Lowlands of Michigan, a wet, flat plain composed of waterlain tills, lacustrine deposits, or both. The polygonal patterned ground is interpreted as a possible relict permafrost feature, formed in the Late Wisconsin when this area was proximal to the Laurentide ice sheet. Cold-air drainage off the ice sheet might have pooled in the Saginaw Lowlands, which sloped toward the ice margin, possibly creating widespread but short-lived permafrost on this glacial lake plain. The majority of the polygons occur between the Glacial Lake Warren strandline (∼14.8 cal. ka) and the shoreline of Glacial Lake Elkton (∼14.3 cal. ka), providing a relative age bracket for the patterned ground. Most of the polygons formed in dense, wet, silt loam soils on flat-lying sites and take the form of reticulate nets with polygon long axes of 150 to 160 m and short axes of 60 to 90 m. Interpolygon swales, often shown as dark curvilinears on aerial photographs, are typically slightly lower than are the polygon centers they bound. Some portions of these interpolygon swales are infilled with gravel-free, sandy loam sediments. The subtle morphology and sedimentological characteristics of the patterned ground in the Saginaw Lowlands suggest that thermokarst erosion, rather than ice-wedge replacement, was the dominant geomorphic process associated with the degradation of the Late-Wisconsin permafrost in the study area and, therefore, was primarily responsible for the soil patterns seen there today. *Key Words: electrical resistivity, glacial lake plain, patterned ground, Pleistocene permafrost, soils.*

我们在密歇根州的萨吉诺低地发现，绘制，并描述分析了一块具有广泛区域（大于 1020 平方公里）的成形土，它是由水成碛或湖成沉积，或者两者兼有而组成的湿润，平坦的平原。具有多边形图案的地面被解释为可能的残余冻土特征，形成于晚威斯康星世代，当时该地区接近劳润泰德（Laurentide）冰盖。冷空气消融了冰盖，并有可能在萨吉诺低地集中，该低地的坡度向冰盖的边缘倾斜，可能在这个冰川湖平原造成了普遍的，但是短暂的冻土。大多数的多边形存在于沃伦冰川湖(14.8 cal. ka)的滨线和艾尔客吞冰川湖(14.3 cal. ka)的岸线之间，为成形土提供了一个相对的年代区段。大多数的多边形成形于致密，潮湿，淤泥质的土壤，具有平坦低洼的特点，构成了多边形网状脉络，其多边形的长轴一般有 150 至 160 米，短轴一般为 60 至 90 米。多边形之间的洼地，在航片中往往显示为暗色的环状线性体，通常略低于它们所依附的多边形中心。这些多边形间洼地的某些部分被无碎石的砂质土壤沉积物所填充。萨吉诺低地的成形土具有微妙的地貌和特殊的沉积特征，这一切表明，在该研究地区，与晚威斯康星世代冻土退化有关的主要地貌过程是热量喀斯特，而不是冰缘置换，这是构成我们现在看到的土壤特征的主要原因。*关键词：电阻率，冰川湖平原，成形土，更新世冻土，土壤。*

Para este artículo, identificamos, cartografiamos y caracterizamos una vasta área (>1.020 km^2) de terreno con superficies reticuladas en las Saginaw Lowlands de Michigan, región de llanuras húmedas, planas, compuestas de *tills* agradados por las aguas o depósitos lacustres, o ambos. El suelo de patrones poligonales se interpreta quizás como un rasgo relicto del permagel, formado en el Wisconsin Tardío cuando esta área estaba en el borde del casquete de hielo Laurentino. El drenaje de aire helado hacia la periferia del casquete podría haber afectado las Saginaw Lowlands, cuya pendiente se orientaba hacia el borde del hielo, posiblemente creando sobre esta planicie de lago glacial amplias aunque efímeras extensiones de permagel. La mayoría de los polígonos se encuentran entre el límite del Lago Glacial Warren (∼14.8 cal. ka) y la costa del Lago Glacial Elkton (∼14.3 cal. ka), lo cual

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rinde un intervalo de edades para el terreno poligonal. La mayor parte de los polígonos se formaron en suelos franco limosos, densos y húmedos, en sitios planos, y adoptan la forma de redes reticuladas en las que los ejes mayores de los polígonos tienen entre 150 y 160 m y los ejes cortos de 60 a 90 m. Las depresiones someras que forman los lados de los polígonos, con apariencia de líneas oscuras curvadas en las aerofotografías, son típicamente menos elevadas que el centro de los polígonos que ellas enmarcan. Algunas porciones de estas depresiones interpoligonales están rellenas de sedimentos de limos franco arenosos, sin gravas. La morfología suave y las características sedimentológicas de los terrenos poligonales de las Saginaw Lowlands sugieren que, más que la sustitución del hielo acuñado, la erosión termokárstica fue el proceso geomórfico dominante asociado con la degradación del permagel del Wisconsin Tardío en el área de estudio y, en consecuencia, fue la responsable primaria de los patrones de la superficie del suelo que se observan allí en la actualidad. *Palabras clave: resistividad eléctrica, planicie de lago glacial, suelo reticulado, permagel pleistocénico, suelos.*

In mid-continent North America, patterned ground, commonly attributed to paleo-permafrost, has been identified in and around the area once covered by the Laurentide ice sheet (Figure 1). The features described in studies from this area included ice-wedge casts, pingo scars, and patterned ground. Although a permafrost genesis for many of these sites and features has been questioned (Black 1976), it is now generally accepted that most of the patterned ground features in the midcontinent are associated with Late Glacial permafrost conditions (Johnson 1990).

Patterned ground has been reported in all the states that border Michigan and in Ontario, Canada (Figure 1). Patterned ground in Michigan was recognized nearly four decades ago by Brunnschweiler (1969) and was subsequently studied by two of his students (Tillema 1972; Lusch 1982), both of whom attributed the patterned ground to thermal-contraction cracking of paleo-permafrost. Tillema (1972) confined his study to a relatively small area ($\sim$194 km^2) in the west-central part of the Saginaw Lowlands of Lower Michigan. Lusch (1982) mapped the nonsorted patterned

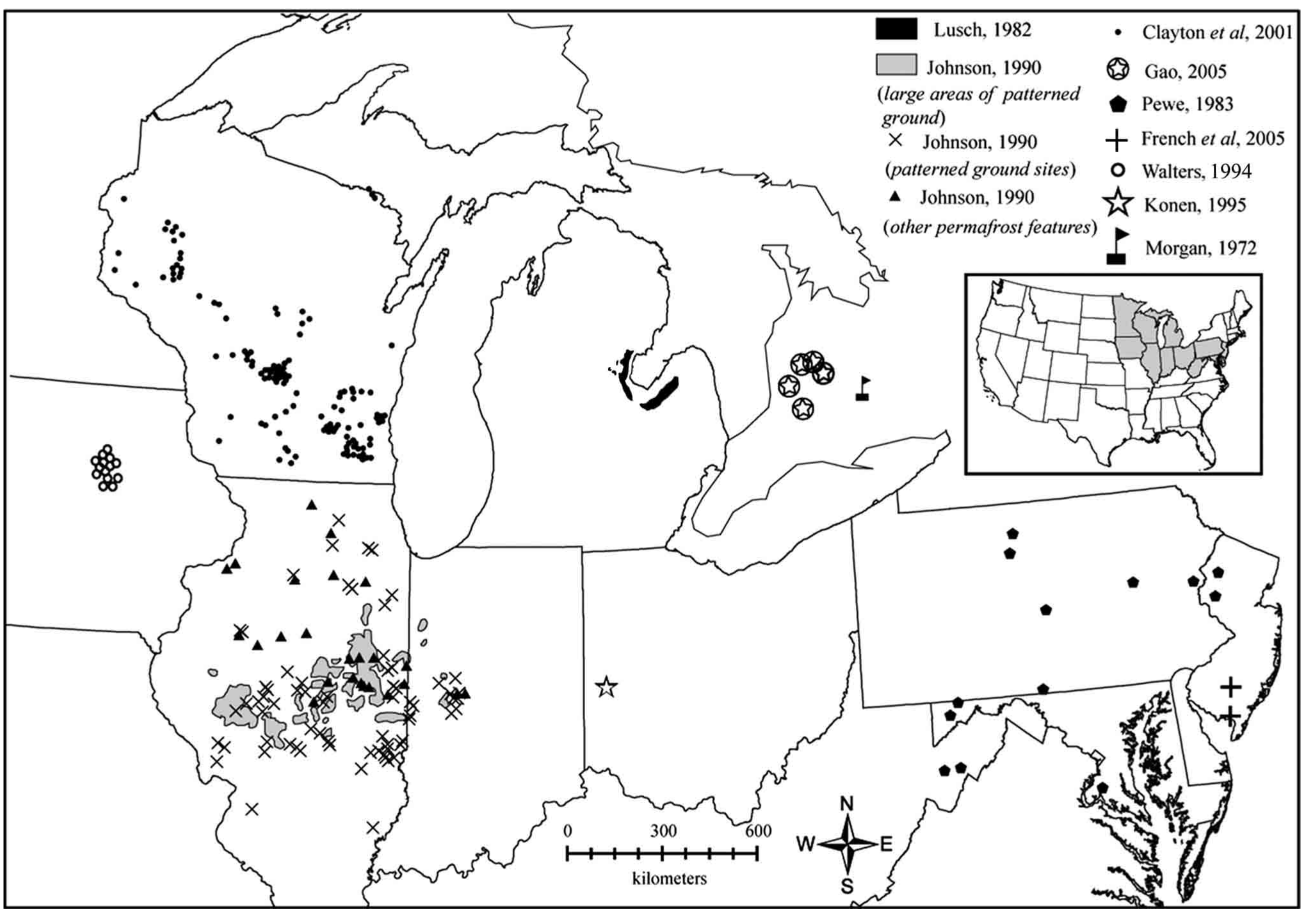

Figure 1. Documented occurrences of permafrost and periglacial features in the midwestern and eastern United States.

ground (cf. Washburn 1956) across a much larger area (>900 km^2) within the Saginaw Lowlands, making it the second most extensive area of documented, contiguous patterned ground in the North American Central Lowlands, behind that mapped in central Illinois (Johnson 1990).

Patterned ground in midlatitude locations like Michigan has been increasingly documented on aerial photographs. Numerous studies (e.g., Svensson 1964) have documented widespread patterned ground in former periglacial regions; most of these patterns are inconspicuous at ground level. In the Great Lakes region, Morgan (1972) utilized aerial photography to describe patterned ground near Kitchener, Ontario. Subsequent studies combined aerial photography and geophysical investigations to delineate and characterize similar features (Greenhouse and Morgan 1977; Lusch 1982). Recent studies have employed ground-penetrating radar (GPR; Hinkel et al. 2001), soil electromagnetic induction measurements (Cockx et al. 2006), high-resolution imagery, or combinations of all three methods (Fortier and Allard 2004) to describe and interpret patterned ground.

We reexamined the patterned ground in the Saginaw Lowlands because (1) georeferenced digital data not previously available, such as soil maps, terrain elevation, and aerial imagery, are now easily accessible; and (2) the geotechnologies available for characterizing patterned ground have vastly improved since 1982. Thus, the purpose of this study is to document, describe, and map the extent of patterned ground in the Saginaw Lowlands of Lower Michigan. After doing so, we offer a hypothesis as to the origins of these features.

Study Area

The Saginaw Lowlands is a low-relief, poorly drained physiographic region surrounding Saginaw Bay in east central Lower Michigan (Figure 2). The regional slope, toward the bay, is typically less than 2 percent; elevations range from 176 to 274 m above sea level. This area was glaciated by the Saginaw Lobe of the Laurentide ice sheet, but the topographic and edaphic character of the Saginaw Lowlands is primarily the result of its repeated inundation by a series of proglacial lakes during the waning phases of the Late Wisconsin substage of the Pleistocene Epoch, as the ice-proximal landscape sloped toward the ice front (Leverett and Taylor 1915; Karrow and Calkin 1985; Karrow 1989; Larson and Schaetzl 2001).

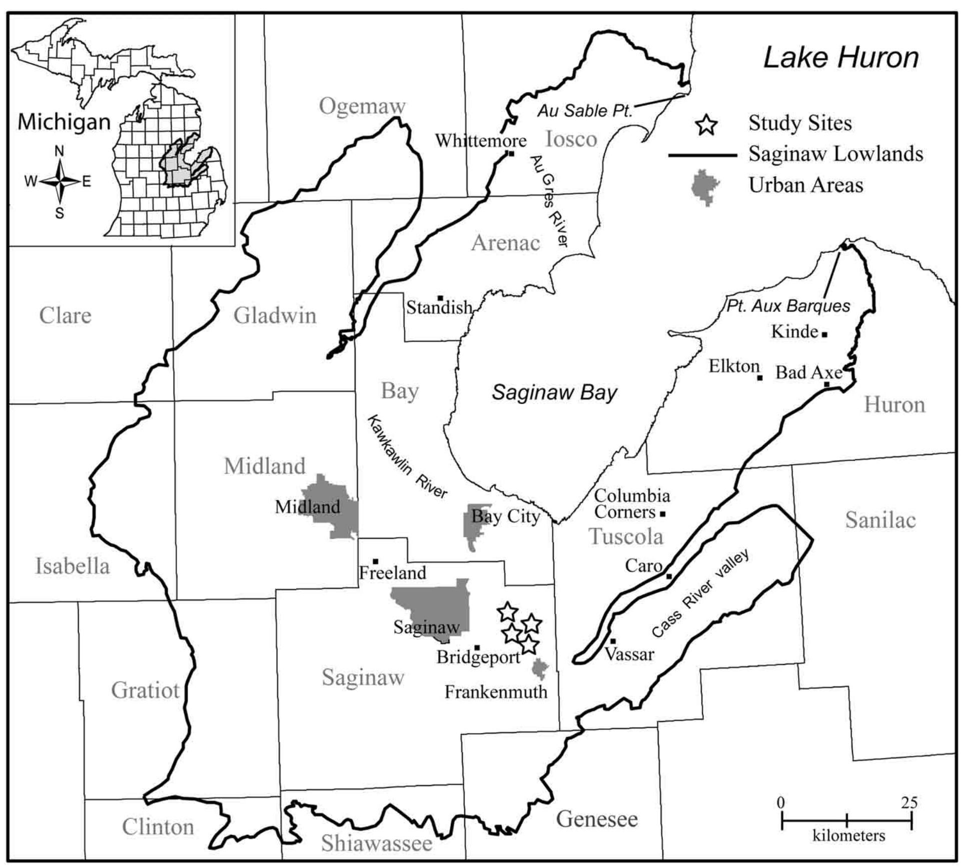

Figure 2. Map of the study area—The Saginaw Lowlands physiographic region.

Given the evolution of the Saginaw Lowlands, we defined the extent of this physiographic region as the terrain proximal to Saginaw Bay that was inundated by any of the Late Wisconsin proglacial lakes. Most of the regional boundary is delimited by the highest proglacial lake strandlines of Early Lake Saginaw and Lake Saginaw, as well as segments of the high Lake Warren shoreline. At the northern and northeastern ends of the region, these Late Wisconsin strandlines are quasi-parallel to, and some distance inland of, the modern shoreline of Saginaw Bay (Figure 2). In these areas, the Saginaw Lowlands margin was delimited by local watershed boundaries (Michigan Department of Environmental Quality 1998) that provided topographically based landward extensions of the line connecting Au Sable Point (Iosco County) with Pointe Aux Barques (Huron County), which was chosen to separate Saginaw Bay from Lake Huron (Figure 2).

Because of repeated lacustrine inundation, most topographic features in the Saginaw Lowlands are subtle. The most prominent landform in the region is the Port Huron Moraine, which marks a Saginaw Lobe readvance (Blewett 1991). In this part of Michigan, the Port Huron Moraine trends parallel to the modern Saginaw Bay shoreline. The greatest topographic expression of the moraine occurs on the northwest and southeast margins of the Saginaw Lowlands, where it was deposited subaerially (Leverett and Taylor 1915; Blewett 1991). Local relief in these portions of the moraine is 25 to 35 m. Across the middle of the Saginaw Lowlands, the Port Huron Moraine was waterlain (Dreimanis 1979, 1988; Kalm and Kadastik 2001) and subsequently beveled by wave action (Leverett and Taylor 1915). This portion of the moraine is topographically smoother than the subaerially emplaced segments and exhibits much lower local relief (1–3 m). Other prominent topographic features in the region include segments of the numerous proglacial lake strandlines, preserved as erosional, wave-cut nicks and benches or as low, sandy ridges. Numerous vegetated, inland sand dunes, most dating to the period immediately after the postglacial lakes had drained, occupy scattered areas of the Saginaw Lowlands (Arbogast et al. 1997; Arbogast and Jameson 1998).

The majority of the soils in the Saginaw Lowlands formed in the silt loam and silty clay loam sediments (mostly till) that dominate the region and in the less extensive glaciolacustrine clays that were deposited in deep pools of the proglacial lakes. Many of these sediments are very dense in the subsoil, causing infiltrating water to frequently perch on a Cd horizon. Thus, soils in this region are wet not only because of low slopes and a high regional water table but also because of perched water on slowly permeable substrates. Dry, sandy soils dominate a few areas, however, especially those occupied by dunes and in parts of the Cass River valley, where glacial outwash and lacustrine sand deposits abound. More than 75 percent of the soils in the region are somewhat poorly drained or poorly drained. The majority of modern land use is agricultural (corn, soybeans, winter wheat, and sugar beets predominate), made possible by subsurface drain tiles and deep drainage ditches. Prior to European settlement, the vegetation was characterized by hardwood and conifer swamps, grassland, and to a lesser extent, peat bogs (Frelich 2002). The climate is humid continental but is locally influenced by Saginaw Bay. The mean annual air temperature at the City of Saginaw from 1961 to 1990 was 7.2°C, and the mean annual precipitation over the same period was 762 mm (Owenby et al. 1992).

Materials and Methods

Polygon Mapping and Characterization

Our goal was to map the extent of and characterize the nonsorted, polygonal patterned ground (cf. Washburn 1956, 1980) that occurs in the Saginaw Lowlands. Closed-net polygons, which typify the patterned ground here, are particularly evident on aerial photos of this area (Figures 3A–3C). The photomorphic traits of the patterned ground are due primarily to differences in soil moisture and organic matter content, which make the interpolygon swales appear darker (Konen 1995). From the extensive, high-quality imagery that was available for the region, we chose to use the National Aerial Photography Program (NAPP) digital orthophoto quads (DOQs), taken in March and April of 1997 to 2000, as our main data source. These 1:40,000-scale, color-infrared, leaf-off images have a nominal spatial resolution of 1 m. We also consulted a complementary set of imagery to ensure that our results were not biased by the quality of the NAPP photos or the particular crop cover that was present at the time the NAPP images were acquired. The second set of photos was acquired in May 1975 by the National Aeronautics and Space Administration (NASA High Altitude Mission 309) and closely matched the seasonal and weather conditions of the NAPP photos but had a nominal scale of 1:120,000.

Aerial photos of recently deglaciated landscapes often display strong photomorphic patterns driven by microtopography (Denny 1968; Way 1978). Our mapping

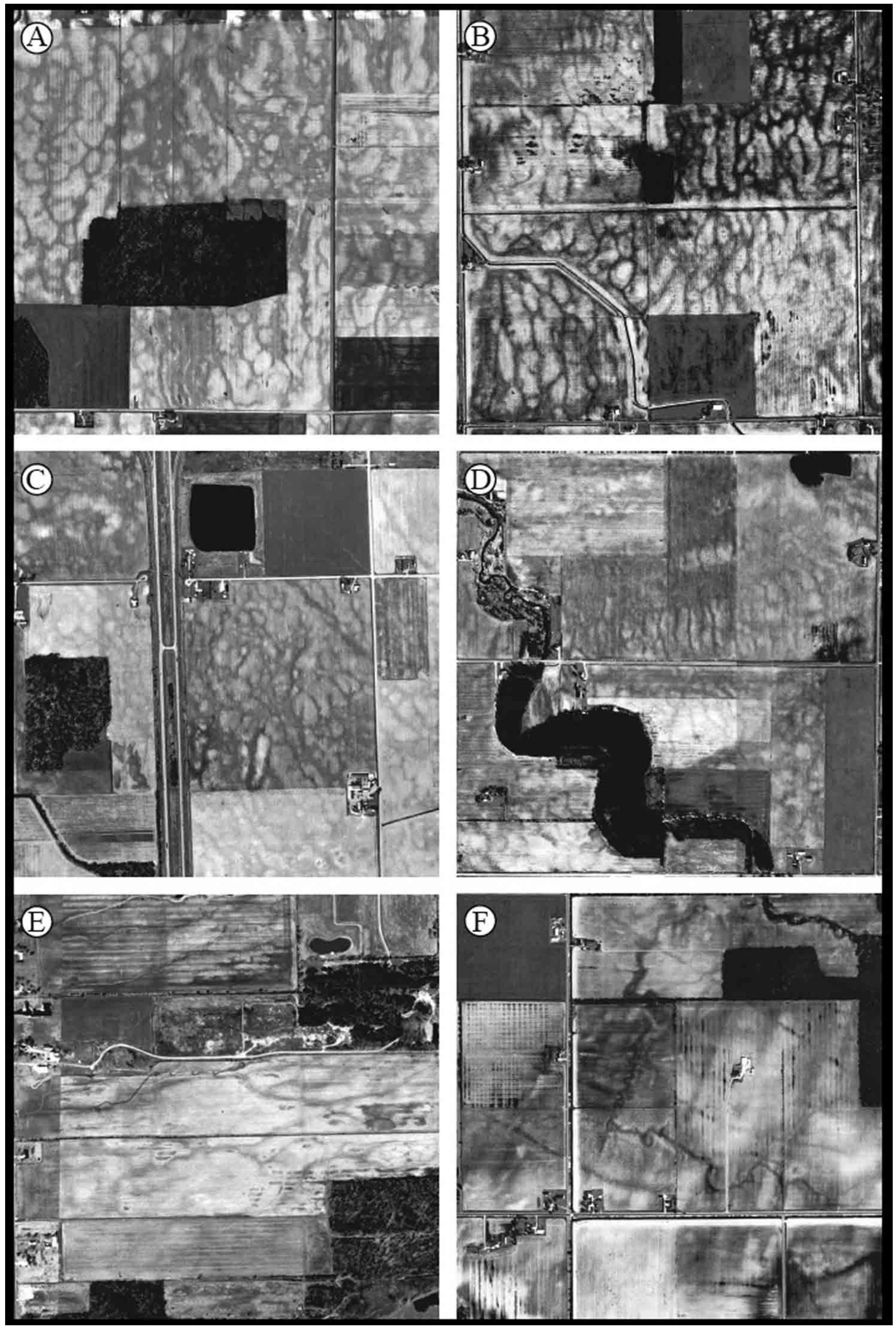

Figure 3. Examples of aerial photographs of the Saginaw Lowlands region, showing examples of strong (A, B) and moderately strong (C, D) patterned ground. Images E and F are examples of other types of soil patterns that are not associated with permafrost processes; that is, they are not mapped as polygonal ground for the purposes of this research. Each image is 1 km^2 in area.

protocol used three criteria to differentiate the nonsorted, polygonal patterned ground from other soil patterns: (1) patterned ground features had to form a reticulate network of mostly closed polygons, (2) interpolygon swales had to exhibit distinct boundaries, and (3) polygons observable within leaf-off woodlots must have swales traceable into adjacent, nonforested fields.

Our mapping began with the NAPP DOQs displayed as county mosaics in ArcGIS 9.1 (ESRI 2005). Our interpretation sampling frame consisted of U.S. Public Land Survey System quarter-sections (~805 m on a side and ~65 ha in extent) that were displayed, in registration, on top of the images. Using the mapping protocol previously defined, each of the 29,591 quarter-sections was classified as having patterned ground present or absent (Figure 3). To be classified as present, at least two or three easily discernable polygons had to occur in the quarter-section. Where patterns were questionable, adjoining quarter-sections were examined to see if unequivocal patterns continued into the area in question (Figure 3).

The initial patterned ground map derived from the DOQs was compared with the NASA imagery in analog form. Using the same mapping criteria, quarter-sections at the boundary between present and absent areas were scrutinized on the high-altitude imagery and appropriate edits to the map were recorded. Following this second phase of image analysis, the revised map was evaluated by an interpreter who had not participated in the initial mapping effort. Patterned areas mapped in the first and second interpretation campaigns were categorized as strong, whereas patterns identified only in the third campaign, by the new interpreter, were deemed moderately strong.

Because most polygons in the study area are ovate in shape, we determined the orientation of polygon long-axes in approximately 250 randomly sampled quarter-sections in the portions of the study area that contained strong patterns. In each of these sampling quadrants, the long axis of each polygon with a clearly defined orientation (i.e., distinctly noncircular) and at least three visible edges—about 1,250 polygons in all—was traced in ArcGIS 9.1. The azimuth of each long-axis feature was subsequently calculated by the geographic information system (GIS) software. The features were grouped into seven geographic clusters and exported for further analysis. Rose diagrams of the azimuths within each cluster were created within MATLAB (The MathWorks, Inc. 2004), and the mean orientation axis was calculated with EZ-Rose (Baas 2000).

We also determined the typical dimensions of approximately 750 polygons scattered more or less randomly across the study area by tracing the lengths of their long and short axes in ArcGIS. Every effort was made to include polygons of all sizes and shapes in this analysis, provided they were distinct on the imagery. Using MATLAB, an ellipse defined by the mean long- and short-axis lengths was plotted on top of a shaded elliptical region representing $\pm$ 1 standard deviation from the mean long- and short-axis lengths. The orientation of the ellipse for each plot presents the mean orientation axis within each geographic cluster.

Elevations in the Saginaw Lowlands vary from 177 m to nearly 300 m above sea level, but the nonsorted nets are virtually nonexistent at elevations below 187 m and have not been observed on terrain above 221 m (Lusch 1982). This range of elevations in the core of the Saginaw Lowlands is closely associated with two proglacial lake shorelines. Thus, the strandlines of glacial Lakes Warren and Elkton were mapped in ArcGIS 9.1, using a combination of the NAPP 1-m resolution, leaf-off, color-infrared DOQs, the U.S. Geological Survey Digital Raster Graphics version of the 7.5-minute topographic maps, and the National Elevation Dataset digital elevation file (3 arc-second). Along the proximal margin of the Port Huron Moraine near the town of Vassar in Tuscola County, the Warren shoreline presents an elevation of about 213 m. Further to the northeast, the Warren strandline rises, in response to isostatic rebound, to about 223 m near the town of Caro and 229 m in the vicinity of the village of Bad Axe in central Huron County. On the northwest margin of the Saginaw Lowlands, no distinct strandlines associated with glacial Lake Warren are obvious on the surface of the Jackpines Delta in Iosco County. Following Burgis (1977), the Warren shoreline was placed along the inner border of the Sand Lake Kettle Chain (the delta surface here has an elevation of about 244 m). In southwestern Iosco County, a weakly developed glacial Lake Warren erosional bluff occurs at about 236 m on the north side of the Au Gres River and at 229 m near the village of Whittemore.

The glacial Lake Elkton strandline occurs at 189 m in the center of the Saginaw Lowlands (e.g., near Bridgeport or Freeland in Saginaw County). To the northeast, near the village of Columbia Corners in Tuscola County, the Elkton shoreline occurs at 194 m. East of the village of Elkton in Huron County, the Elkton shoreline has rebounded to an elevation of 200 m. Near the village of Kinde in north central Huron County, the Elkton strand reaches its maximum elevation of 206 m. The Elkton water plain is similarly warped on the northwest side of the Saginaw Lowlands. The Elkton strand has an elevation of about 191 m where it crosses the Kawkawlin River in Bay County. To the north, near the town of Standish in Arenac County, the Elkton shoreline occurs at 195 m. The Elkton strandline reaches its maximum elevation of 206 m at the north line of Arenac County and continues at that elevation into Iosco County.

Statistical and GIS Methods

We characterized the areas of patterned versus non-patterned ground in terms of soil texture class, natural soil drainage class, soil map unit slope, and the drainage index (DI). The dominant soil texture classes were aggregated from soil management groups (Mokma, Whiteside, and Schneider 1974) in the Natural Resources Conservation Service (NRCS) SSURGO digital soil files (http://soildatamart.nrcs.usda.gov/). Natural soil drainage class and map unit slope were also derived from SSURGO data. The DI is an ordinal-scale variable of soil wetness (Schaetzl 1986; Schaetzl et al. 2009).

We used Hawth's Analysis Tools extension for ArcMap (Beyer 2006) to create 4,000 random points within the Saginaw Lowlands study that were not within 100 m of another point or located within urban/industrial or open water areas. Of the 4,000 random points, 383 were within areas mapped as having strong or moderately strong patterned ground.

Soil textures (e.g., loamy, silty clay loam) are nominal (grouped) data, so we used a contingency table analysis (chi-square) to test for significant relationships between the patterned and nonpatterned subsets. Both the natural soil drainage class (e.g., poorly drained or well drained) and the slope categories (e.g., 0–3 percent, 6–10 percent) are ordinal data types; thus the Mann–Whitney U test was used to calculate significance values. The DI values range from 0 (driest) to 99 (wettest), but the exact relationship between any two values on this scale, as well as their units, is not defined (Schaetzl 1986; Bragg, Roberts, and Crow 2004), nor is the underlying distribution of the data understood. As a precaution, therefore, we used the Mann–Whitney U test to evaluate the statistical significance between DI values of the two sample populations. Prior to analysis, the DI values were aggregated into ten groups to reduce the problems associated with comparing vastly uneven group sizes (many individual DI value bins were either empty or only had one member). SPSS software (SPSS, Inc. 2006) was employed to run the statistical tests.

Soils and Sediments: Field and Laboratory Methods

Sites for ground-based soil investigations were initially chosen based on aerial photographs. Forested areas with strong polygonal patterns were targeted to minimize human disturbance. From a large set of initial sites, we chose three areas (Figure 4) for more detailed work based on preliminary field observations and access permissions from cooperative landowners. At each site, soil-boring transects were completed across several polygons, beginning at the polygon center, across a swale (interpolygon low area), and onto the

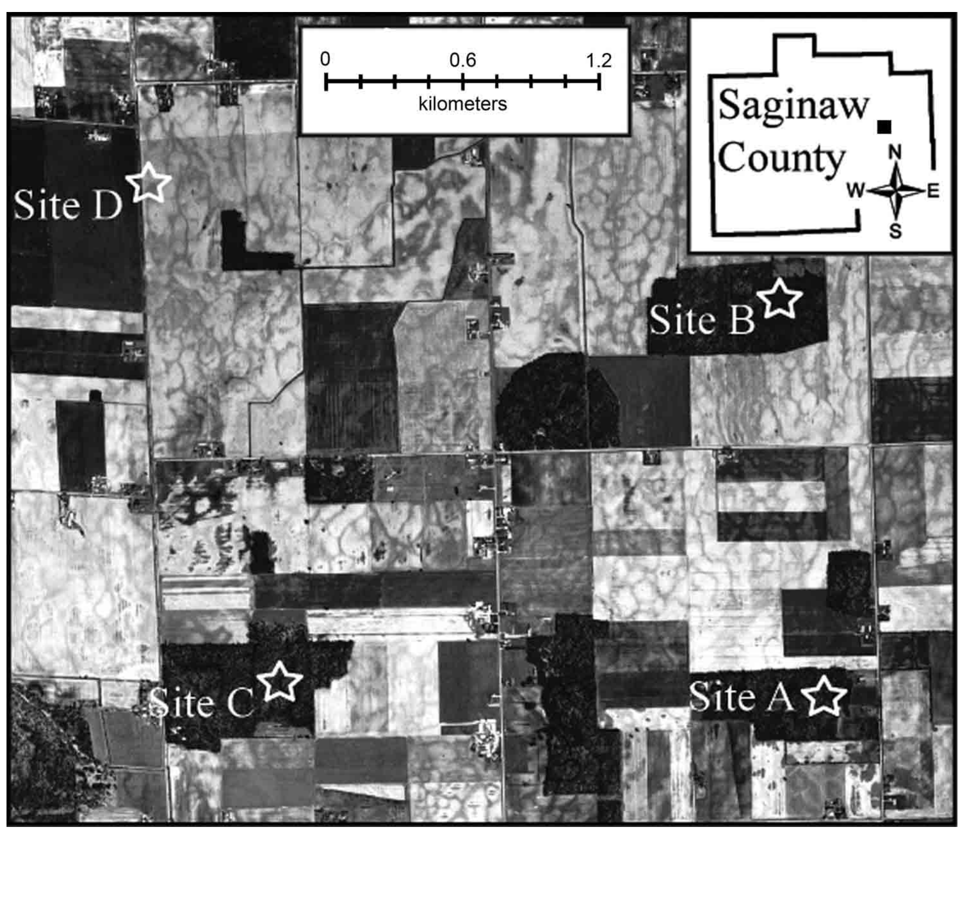

Figure 4. Locations of the three main study sites for this research, plus the site of the ice-wedge cast (Site D), on a leaf-off, aerial photograph background.

adjacent polygon center. Using 3-inch-diameter hand augers, we excavated to 1 to 2 m depths at stations spaced roughly 5 to 12 m apart. At least one auger sample was positioned at the center of the two polygons, with auger sites more clustered in the swales. Differences in soil texture, color, coarse fragment content, and sediment type were recorded for each auger location, along with relative elevation measured with a stadia rod and handheld level. In all, there were five transects at three study sites, crossing eleven polygons and six swales.

Electrical resistivity (ER) was used to identify and image lateral and vertical variations in soil and sediment properties along three transects. Using the reasonable assumption of little variation in the conductivity of pore water, the electrical resistance of soils is primarily a function of texture and moisture content (Reynolds 1997). Although GPR can be used for such characterizations, it does not operate well in clay-rich terrain like the Saginaw Lowlands. We employed both dipole-dipole and Wenner electrode configurations (Reynolds 1997). The Wenner array is most sensitive to vertical variations in electrical resistivity, while the dipole-dipole array is especially sensitive to lateral discontinuities. ER measurements were conducted at three study sites, generally along and parallel to an auger transect, allowing us to use the auger data as ground truth for the ER data (Figure 4). We employed an AGI Supersting eight-channel, portable earth resistivity system (Advanced Geosciences, Inc., Austin, TX) with multicore cables and either twenty-eight or forty-two electrodes. Data were collected in standard and roll-along modes using electrode spacings ranging from 0.5 to 1 m. The ER data were topographically corrected using the field-collected elevations and inverted with the AGI EarthImager software, using default settings (more customized inversion settings yielded substantially similar results).

Ground truth data on soil texture (obtained from the auger sites) were needed to interpret our ER data correctly, as were data on soil water content. To obtain the latter, we used an extended auger to collected soil samples every 25 cm to a depth of 3.7 m from one location at study Site B. The weight of each field-moist soil sample (stored in sealed bags) was recorded within twelve hours of sample collection. Samples were dried at 105°C and gravimetric soil water contents were determined.

Soil pits were excavated at six different locations across three study sites (Figure 4). All pits were located along transect lines; three within polygon centers and three within nearby swales. Guided by the auger and ER data, the three polygon-center pits were located on sites that had a thick sand cap above dense till (Site B), a thinner sand cap above the same till (Site A), and no sand cap (i.e., silt loam till extended to the surface, Site C). All pits were excavated to the C horizon, although in many pits the upper C horizon lay below the water table. Soil profiles exposed in the pit faces were described according to NRCS guidelines (Soil Survey Division Staff 1993; Schoeneberger et al. 2002). Samples of 500 to 700 g were taken from each genetic horizon, dried in a 30°C oven, ground using a mortar and pestle, and then passed through a 2-mm sieve to remove gravel. After removal of excess organic matter with H_2O_2, the particle size distribution of the 0 to 2,000 μm fraction was determined using a Mastersizer 2000E laser particle size analyzer (Malvern Instruments, Inc., Southborough, MA). The Trask sorting coefficient

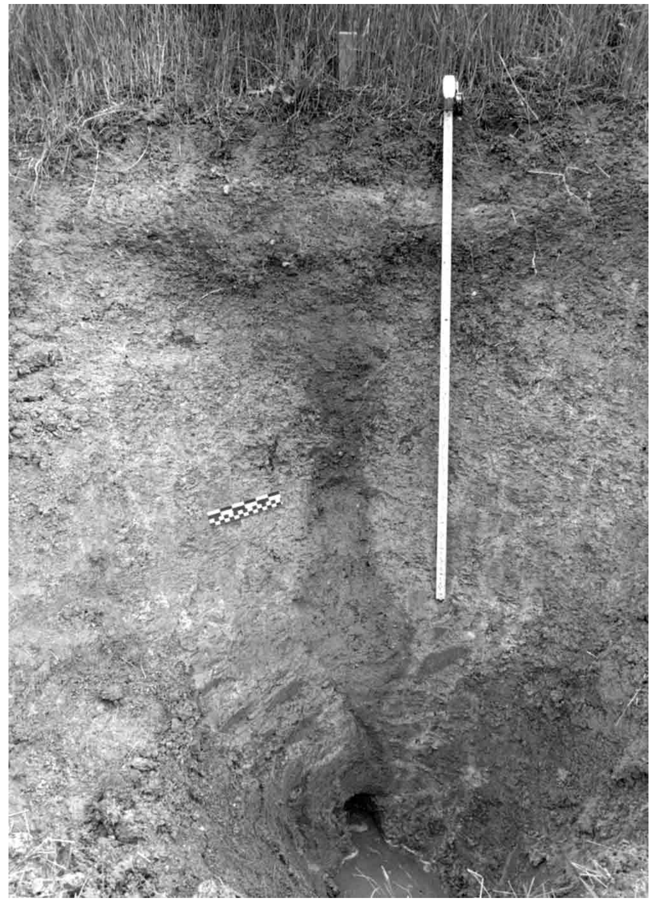

Figure 5. Fossil ice-wedge cast exposed in the east face of a roadside ditch near Bridgeport, Michigan (Site D). The wedge of well-sorted, medium sand penetrates a sandy clay loam-to-clay loam diamict. Note the small cavity at the bottom of the exposure formed by groundwater piping of the more transmissive wedge sediments. The tape measure = 1 m; the small scale at the left = 15.2 cm.

(S_o), the square root of the ratio of the 75 percent quartile size value (D_{75}) to the 25 percent quartile value (D_{25}), was computed from the particle size data (Trask 1932). 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).

Finally, we excavated a pit at the roadside ditch site (our Site D; Figure 4) where Lusch (1982) had previously observed and sampled a feature he interpreted as an ice-wedge cast (Figure 5). Excavation of the heavily vegetated ditch face was not possible due to the landowner's concern about gully erosion (the ditch had been recently cleaned of vegetation when Lusch studied the area). Therefore, a soil pit was excavated 2 m from the ditch edge after several ER transects and subsequent auger holes across the site identified the location of a subsurface sand body. We excavated, described, and sampled two pit faces, each less than 2 m east of the original ice-wedge cast, and roughly 50 cm apart.

Results and Discussion

Patterned Ground: Extent and Characteristics

Patterned ground in the Saginaw Lowlands exists in a variety of forms and with widely varying strengths of expression (Figures 3 and 6). Most of the patterns in the Saginaw Lowlands have similar photomorphic properties to those described in Ontario (Morgan 1972), Illinois (Johnson 1990), and Ohio (Konen 1995), where they exist on similar soils. Strong or moderately strong reticulate mesh patterns cover 5.3 percent of the study area and occur in three somewhat distinct groups that generally parallel the current and past shorelines in the region: (1) a small cluster in Iosco County, which extends nearly to Saginaw Bay (~82 km^2); (2) an arcuate band, trending north from the west side of the City of Saginaw into Arenac County (~424 km^2); and (3) a second curving band, trending from the east side of the city of Saginaw northeast into Huron County (~357 km^2), where it becomes very patchy (Figure 6).

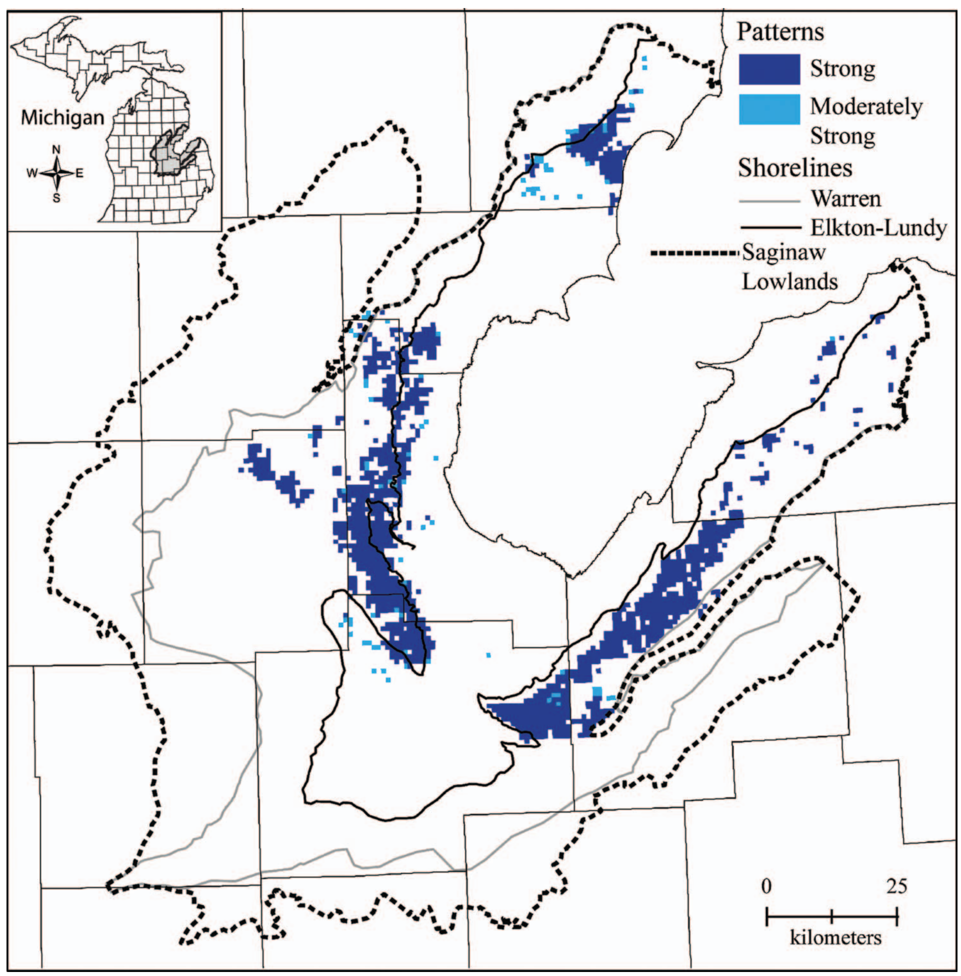

Figure 6. Extent of patterned ground, both strongly expressed and moderately expressed, within the Saginaw Lowlands. Locations of two major proglacial lake shorelines are also shown.

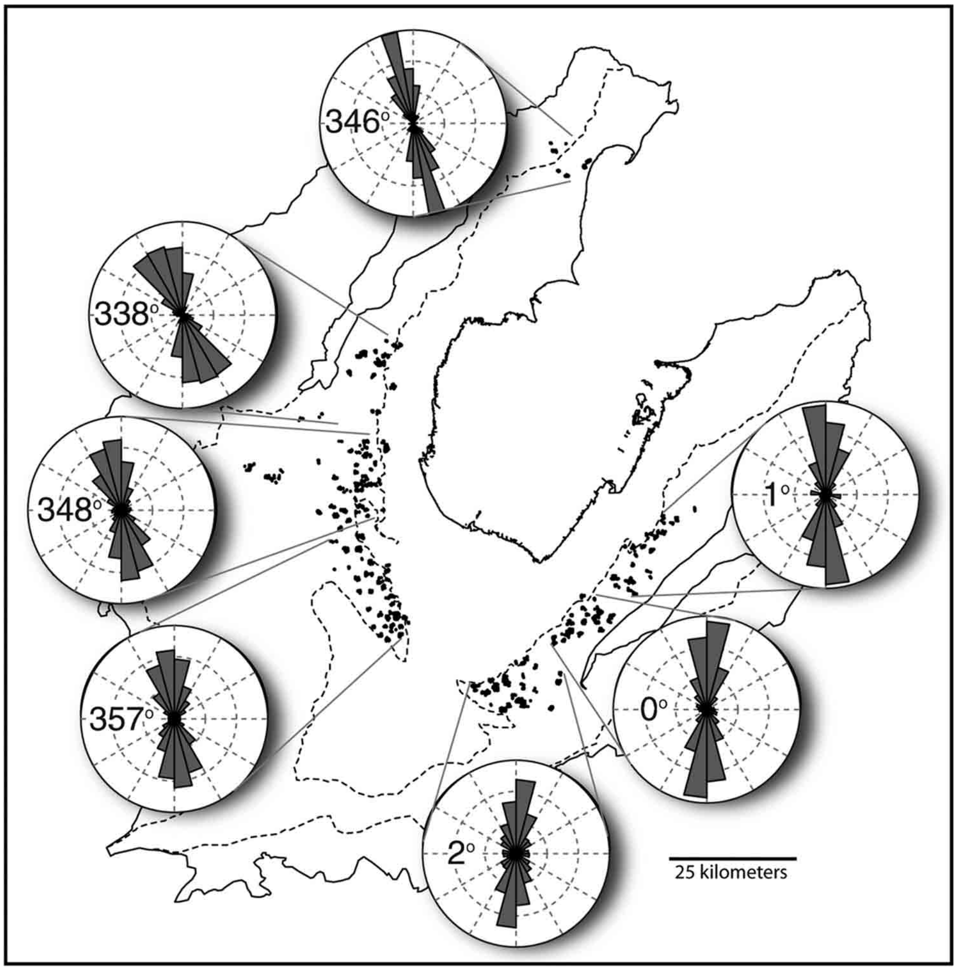

Figure 7. Mean orientations of a sample of patterned ground polygons, grouped into seven geographic clusters.

It is likely that patterned ground also occurred within the city limits of Saginaw, but the built landscape made our mapping efforts there futile. Our map of the patterned ground distribution (Figure 6) corresponds well with the previous work by Lusch (1982), although our study area is larger than his, and thus we mapped a much larger extent of it. Out of the 29,591 quarter-sections in the Saginaw Lowlands, 5.0 percent (1,485) contained strongly patterned ground and 0.3 percent (90) contained moderately strong patterns. Altogether, we mapped 1,020 $km^2$of patterned ground in the Saginaw Lowlands. Many of the areas mapped as absent contain faint patterns that could have been included in the present category, had our mapping protocols not been so deliberately conservative.

In Saginaw and Tuscola Counties, in the center of the Saginaw Lowlands, most of the patterned ground lies between the shorelines of glacial Lakes Elkton (lower) and Warren (upper; Figure 6; Lusch 1982). To the north (in Arenac and Iosco Counties) and northeast (in Huron County), some patterns also occur below the Elkton strandline. In Tuscola County, southeast of the main zone of patterned ground, a few polygons also occur above the Warren shoreline, on the proximal edge of the Port Huron Moraine. The entire swath of patterned ground in the central Saginaw Lowlands is overwhelmingly dominated by soils formed in silty sediments—tills and water-reworked tills. To the north in Iosco County, the patterned ground is restricted to areas lacking deep sandy soils that dominate this area. The southwestern segment of the patterned ground area in Tuscola County formed on the waterlain portion of the Port Huron Moraine. This very low-relief landform is where our study Sites A through D (Figures 2 and 4) are located. The patterns in Bay, Midland, and Saginaw Counties are also on the surface of the waterlain portion of the Port Huron Moraine. The northern portion of this region is composed of silty soils, capped with many small sand dunes (Arbogast et al. 1997). In this terrain, the patterned ground occurs only on the wet, silty soils between the dunes.

The majority of the patterns in the study area are elliptical in shape (Figures 3A–3C). The long-axis orientation of these features is remarkably consistent among the thousands of polygons in the study area (Figures 3B, 3C, and 7). Most of the polygon long axes are aligned nearly north–south, despite the fact that regional slopes, however gentle, are everywhere toward Saginaw Bay, and thus vary markedly across the region. We have no explanation for the nearly constant north–south orientation of these polygons, nor can we explain the very low degree of azimuth variation that exists among the orientations.

Most of the polygons in the study area are roughly 1 ha in size, about 150 to 160 m long and 60 to 90 m wide (Figure 8). The variation in width and length, shown by the width of the gray band in Figure 8, varies notably across the region. Polygon width is less variable than is length, especially in the long, narrow polygons in Iosco County. Overall, polygon size and orientation across the region are remarkably uniform, which might be related to the uniformity of parent material texture, wetness, and slope in this area (Figure 9).

In the Saginaw Lowlands, the polygons and swales are more clearly defined on the ground in undisturbed settings, such as woodlots (Figures 4 and 10). Throughout the region, the polygons are high-centered with topographically lower swales bounding the polygon interiors. In our woodlot sites, relative elevation differences between the polygon interiors and swales ranged between ~20 cm over a ~30 m distance to ~1.5 m over a ~60 m distance (Figure 11). Many swale areas in the woodlots are treeless because of persistent standing water in spring and fall (Figure 10). Many polygon centers in our woodlot sites had a thin cap of sandy material. Figure 12 shows two high-centered polygons truncated by a roadside ditch.

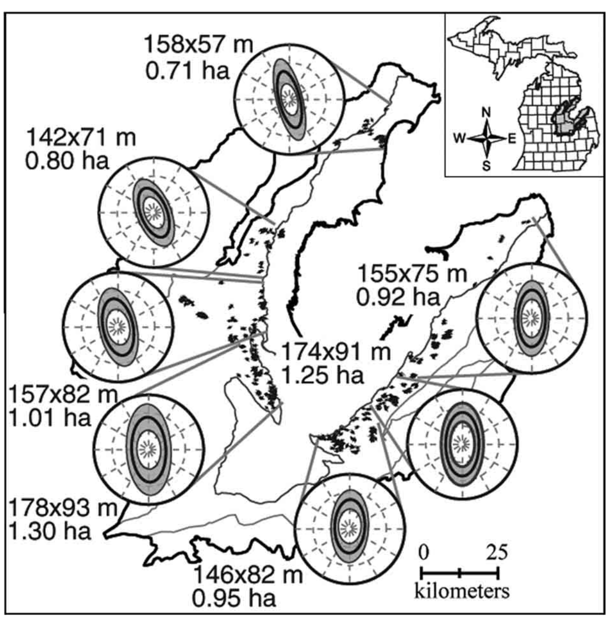

Figure 8. Mean sizes (black line) plus one standard deviation (gray envelope) and orientations of a sample of patterned ground polygons, grouped into seven geographic clusters.

Patterned Ground: Relationships to Soils and Sediments

We examined whether the soils at 4,000 randomly positioned points in the patterned and nonpatterned areas were statistically different along four different data axes: texture class, natural soil drainage class, soil map unit slope, and drainage index (Table 1). We rejected the null hypothesis (h_o = soils in patterned and nonpatterned areas are similar) for three of the four variables examined (DI values were the exception), suggesting that the patterned ground had formed on significantly different regolith than that found in nonpatterned areas. More than 70 percent of the sample points in the patterned areas are on loam and silt loam soils, but these types of soils comprise only about 36 percent of the sample points in nonpatterned areas (Figure 9A). Conversely, many sample points in nonpatterned areas are on sandy soils (Figure 9A). It is unclear whether the soil relationships associated with patterned versus nonpatterned areas are due to (1) sand burying patterns that might exist in the subjacent silty and loamy soils, or (2) the lack of formation of such patterns in all but silty and loamy soils. That is, we do not know whether the sand cap (where it exists over the silty tills) pre- or postdates the formation of the patterned ground. This relationship could provide a fruitful area for future research.

Figure 9C illustrates the dominance of somewhat poorly and poorly drained soils in the Saginaw Lowlands; most of the patterned ground occurs on these types of soils. A great majority of the sample points on better drained soils are located in nonpatterned areas, whereas almost all of the sample points in patterned ground areas are on the somewhat poorly and poorly drained soils (Figure 9C). Interestingly, almost no sample points in patterned areas are on very poorly drained soils, suggesting that this type of environment might be too wet for patterned ground to form or be preserved. This observation is also supported by the DI data (Figure 9D).

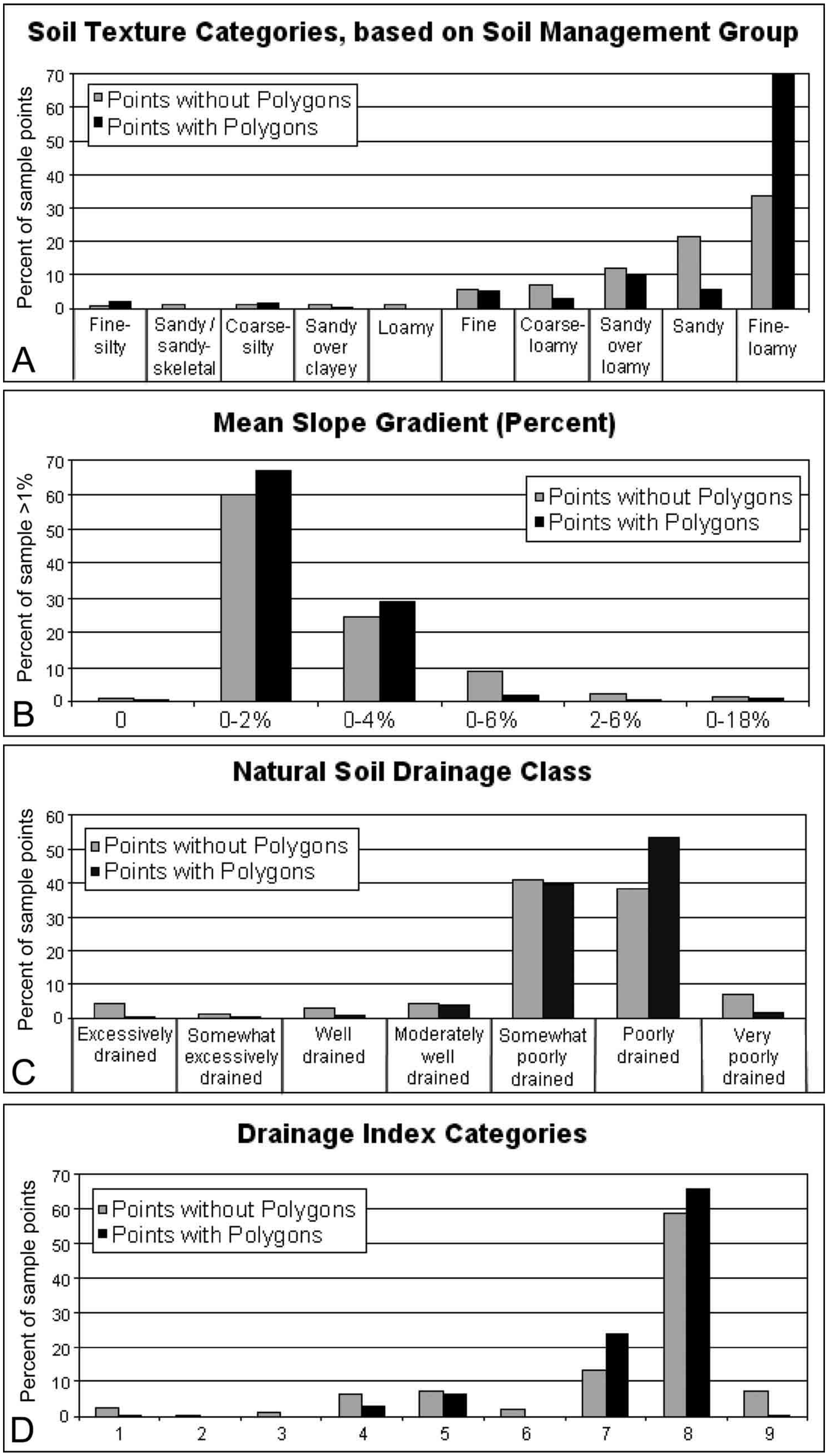

Figure 9. Mean data values for the soils and sediments of patterned versus nonpatterned terrain in the study area, based on a random sample of 400 points. (A) Soil texture classes, based on soil management group classifications. (B) Mean map unit slope, defined by the "Representative Slope" variable in the Natural Resources Conservation Service SSURGO-2 database. (C) Natural soil drainage class, as defined in SSURGO. (D) Drainage index (DI) values (Schaetzl et al. 2009): 0: DI missing/undefined; 1: 0–15; 2: 16–25; 3: 26–35; 4: 36–45; 5: 46–55; 6: 56–65; 7: 66–75; 8: 76–85; 9: 86–99. Soils with DI values of 0 are extremely dry, and 99 is the wettest value soils can obtain.

Figure 10. Photo of an interpolygon swale at Site B. The low, linear trace, with its dark, heavy silt loam soils is readily visible on aerial photographs (inset) and retains standing water for much of the fall and spring.

The Saginaw Lowlands region is a very low-relief landscape. Not surprisingly, the majority of the soil map units in the region have slope classes of less than 6 percent (Figure 9C). Slope does not appear to be a useful predictor of patterned versus nonpatterned ground, as there is often very little difference between map units of 0 to 3 percent and 3 to 6 percent slope. It is clear (and statistically significant; Table 1), however, that

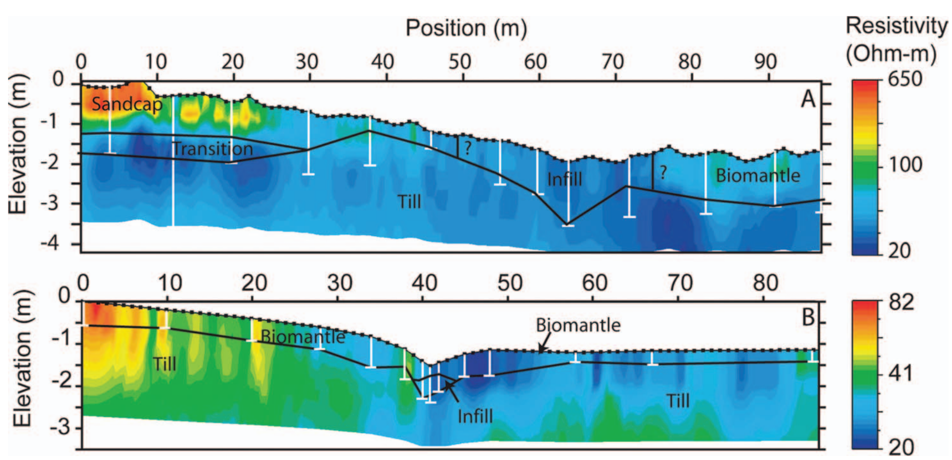

Figure 11. Sedimentological data for two representative transects. Data from hand augering are shown as fence diagrams, overlain on inversions of electrical resistivity data collected using a Wenner configuration. Red areas have higher resistivity and are generally coarser textured or were drier at the time of survey; blue areas reflect wet or fine-textured sediments. (A) Site B transect. (B) Site C transect. Note the different color scales for the two plots.

Figure 12. View of a shallow ditch that intersects the edges of two polygons in the northern part of the study area. Aerial photography (inset) shows that the three troughs at the ditch edge (white arrows) correspond to linear, interpolygon swales in the field.

patterned areas are more common on sites of lowest slope.

In summary, patterned ground in the Saginaw Lowlands is most common, and exhibits its strongest and clearest expression, on somewhat poorly and poorly drained silt loam and loam soils with less than 3 percent slope. Areas with coarser textured soils, especially sands, tend to have no patterns or only poorly developed patterns, as do sites with moderately well-drained or drier soils (Figure 9). Elsewhere in the Midwest, similar patterned ground features tend to occur on sites that have similar types of soils to those found in the Saginaw Lowlands. Johnson (1990) described extensive areas of patterned ground on the flat, wet, silt loam soils in central Illinois. Similar patterns occur on a low-relief landscape in southwestern Ontario, Canada, formed in till described as "sandy silty" (Morgan 1972, 614). The patterned ground described by Konen (1995) in west central Ohio formed on silty clay loam till associated with a wet, low-relief ground moraine.

Soil and Sediment Observations

Our auger transects (Figure 11) revealed well-sorted, fine sandy material in varying thicknesses capping the interiors of many of the polygons. At Site C, the cap was greater than 70 cm thick and fine sandy loam in texture, whereas at Site A the cap had a sand texture and was thinner (32 cm). The thickness of the sand varies slightly across the polygon interiors, probably due to tree uprooting disturbances. At Site B, a 20- to 40-cm-thick sand cap is present in the eastern parts of the woodlot, but it thins and becomes largely absent on the western end. Soil pit (B1) was located in this western area and confirmed the absence of a sand cap. Laboratory data, however, show that the uppermost soil horizons at this polygon interior site had fine sandy loam textures, presumably because of long-term mixing, probably by bioturbation, of a thin sandy mantle into the silty material below. Thus, in this part of the study area, varying thicknesses of fine sand commonly overlie silt loam till. In areas where the sand cap is thin (<50 cm), the amount of silt mixed in from below can be significant.

At depth in all polygon interior sites, we encountered dense, calcareous loam and clay loam till in the C horizon. Horizons immediately above tended to have similar textures but with much lower bulk densities and increased porosities. The lithologic break between the underlying till and the overlying sediment (sand or silt loam cap) was readily detectable in auger holes by the increase in small coarse fragments (~2–6 cm) at the boundary. In some cases, the dense till at depth contained coarsely stratified, fine sand lenses, which we attributed to some degree of water-working beneath proglacial lakes.

The fine sandy loam (or sandy loam) cap was noticeably absent in all the swale sites we examined, remaining generally thin or nonexistent even to several

Table 1. Results of statistical tests on the soils in patterned versus nonpatterned ground areas

Variable in question	Null hypothesis	Significance of pairwise, two-tailed test (p)	Result
Soil texture by soil management group	Textures of soils in patterned areas = textures in nonpatterned areas	0.000	Reject null hypothesis: Textures are different
Natural soil drainage class	Drainage classes of soils in patterned areas = drainage classes in nonpatterned areas	0.000	Reject null hypothesis: Drainage classes are different
Map unit slope	Slopes of soil map units in patterned areas = slopes in nonpatterned areas	0.001	Reject null hypothesis: Slopes are different
Drainage index (DI)	DI values of soils in patterned areas = DI values in nonpatterned areas	0.551	Accept null hypothesis: DI values are not different

meters beyond the topographic edge of the swale. Soils in the swales tended to be organically rich and texturally uniform (silt loam, with <2 percent coarse fragments) in the upper meter, with shallow water tables, just as noted by Konen (1995) in Ohio. A clear lithologic break to the dense and more gravel-rich till below suggested that the material in the swales might have been infilled into some sort of preexisting depression from the adjacent uplands. In some swale locations, coarsely stratified sand lenses were noted at the contact with the subjacent till, supporting this hypothesis. Laboratory results reveal that the swale sediments at Sites A, B, and C all have similar textural characteristics, regardless of the differences between corresponding upland materials (thick, thin, or no sand cap).

Possible Origins of Nonsorted Nets

In general, the genesis of most patterned ground is problematic because similar forms of patterned ground can result from different processes, and a single process can produce dissimilar forms. Indeed, there are more proposed genetic processes than there are recognized types of patterned ground (Washburn 1956, 1973). Morgan (1972) considered surficial drainage along fractures in till as a possible origin for nonsorted polygons. He attributed these fractures to glacial ice movement and noted that some of the patterned ground was aligned nearly parallel to this direction. This suggested origin is untenable in the Saginaw Lowlands, however, because the trends in the net mesh are unrelated to either glacial flow direction or surficial drainage.

Striking examples of nonsorted patterned ground have been reported from southern England (Perrin 1963). There, polygonal and elongated patterned ground was formed on a thin glacial mantle overlying chalk bedrock. The surficial patterns were found to be associated with a ridge-and-trough microtopography on the surface of the bedrock that was attributed to periglacial processes. The glacial sediments in most of the Saginaw Lowlands are more than 30 m thick, making it extremely unlikely that bedrock microtopography or jointing could be involved in the formation of the surficial nonsorted nets observed here.

Although the patterned ground in the Saginaw Lowlands appears similar in form to certain ice-stagnation landforms reported by Gravenor and Kupsch (1959) and Parizek (1969), several facts strongly argue that the Saginaw nets are not ice-stagnation features. First, the nets are spatially associated with the Port Huron Moraine, a major ice-marginal landform attributed to active ice readvance throughout the eastern Great Lakes Basin. Second, no other ice-stagnation landforms (e.g., eskers, kames, or kettles) occur within the Saginaw Lowlands. Finally, an ice-stagnation origin could not account for the restricted range of topographic and edaphic conditions associated with the nets, nor could it explain the congruence of the lower elevation limit of most of the patterns with the shoreline of glacial Lake Elkton.

Nonsorted nets can be formed by desiccation cracking (Willden and Mabey 1961; Neal and Motts 1967; Neal, Langer, and Kerr 1968; Neal 1972), but evidence of long-term, severe drought, necessary to form large dehydration polygons, is lacking in the Saginaw Lowlands from the time interval when the patterned ground is thought to have formed (~ Warren to Elkton time). To the contrary, most of the patterned ground in the study area occurs on somewhat poorly drained soils. It is likely that similar or even more poorly drained conditions existed during the waning phase of the Late Wisconsin when several large proglacial lakes occupied parts of the Saginaw Lowlands in succession and elevated the local water table compared to present conditions.

Nonsorted nets can also form on soils rich in smectite, in the form of gilgai microtopography. Gilgai forms from the repeated desiccation and rehydration of expandable clays, causing volume changes of the regolith (Costin 1955; Hallsworth, Robertson, and Gibbons 1955). The swell potentials of most soils in the Saginaw Lowlands are less than 5 percent, however, well below the 30 percent swell capacity typical of gilgai soils. In addition, the area lacks a distinct dry season, which is found in almost all areas where gilgai exist.

Some mudcracks can develop in subaqueous environments. The processes that form these so-called synaeresis cracks are not well understood but might include water expulsion from clay-rich suspensions by internal forces (McLane 1995). Kostyaev (1969) noted that synaeresis cracking can form polygons tens of meters in diameter, but most synaeresis cracks produce an irregular pattern, not the well-developed polygonal mesh associated with the patterns in our study area. Washburn (1973) concluded that this mechanism is relatively unimportant in forming nonsorted patterned ground. Additionally, the large size of the nonsorted polygons in our study area precludes this mechanism as a possible origin.

Nonsorted patterned ground can form by thermal-contraction fissuring of seasonally frozen ground. Active seasonal frost-crack polygons have been reported from midlatitude sites (Washburn, Smith, and Goddard 1963; Washburn 1973; Black 1976). It is doubtful, however, that the large-diameter, reticulate pattern of the Saginaw nonsorted nets is the result of current or former seasonal frost cracking because polygons produced by this process are usually less than 15 m in diameter (Shumskiy and Vtyurin 1966).

Finally, nonsorted patterned ground can form by thermal contraction-fissuring of permafrost and the growth of ice-wedge polygons (Leffingwell 1915, 1919; Lachenbruch 1960, 1961, 1962, 1966; Kerfoot 1972; Mackay 1974). During thermal degradation of permafrost, the enclosed ice wedges thaw or sublimate. The space formerly occupied by the ice wedge can be replaced with adjacent, overlying, or allochthonous materials, forming an ice-wedge cast (Péwé, Church, and Andresen 1969; Murton and French 1993; French 1996). Although ice wedges are best developed in saturated (i.e., high ice content), fine-grained soils with 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 tends to obliterate the wedge form if the ice wedge has not been replaced by transported material.

Genesis of Patterned Ground in the Saginaw Lowlands

Following on the work of Konen (1995) in Ohio, Johnson (1990) in Illinois, and Morgan (1972) in Ontario, we interpret the patterned ground features in the Saginaw Lowlands to most likely be relict permafrost features. Because most of the polygons occur topographically below the Lake Warren shoreline, their formation probably postdates Lake Warren (14,800 calender years ago). The Saginaw patterned ground probably formed on the subaerial landscape as it became progressively exposed as glacial Lake Warren drained. In the central part of the Saginaw Lowlands, the patterns are starkly bounded by the Lake Elkton strandline. This suggests that pattern formation was mostly confined to subaerial (as opposed to subaqueous) surfaces and largely ceased around the time Lake Elkton dropped to the Early Algonquin lake stage about 14,300 cal. years ago (Eschman and Karrow 1985). Thus, if these dates are taken literally, the patterned ground here might have formed during only a 500-year span of time, between 14,800 and 14,300 years ago.

The thermal-contraction cracking of the this short-lived permafrost event might have been induced or intensified by katabatic winds flowing off of the Laurentide ice sheet and pooling in the Saginaw Lowlands, which sloped gently toward the ice margin. As Lake Elkton fell to the Early Lake Algonquin stage (14,300 cal. years ago), most of the subaerial portion of the central Saginaw Lowlands might have been too warm and too distal from the ice margin to continue to thermally crack. Two notable zones of topographically constrained periglacial terrain were also deglaciated at about this time (see white arrows on Figure 13). These proglacial, broad valleys, formed between the ice margin and the periglacial highlands in northeastern Lower Michigan and at the tip of the "thumb" of the Lower Peninsula in Huron County, might have continued to channel cold-air drainage off the ice sheet, explaining the restricted zones of patterned ground that formed below the Lake Elkton strandline in Arenac, Iosco, and Huron Counties.

The average size of the Saginaw polygons (159 × 79 m) is substantially larger than most of the fossil ice-wedge polygons previously reported from elsewhere in North America, northern Europe, or Scandinavia. The average size of fossil ice-wedge polygons reported in North America is 42 × 12 m (Wilson 1958; Wayne 1963, 1967; Péwé, Church, and Andresen 1969; Clayton and Bailey 1970; Lagarec 1973; Walters 1975, 1978, 1994; Johnson 1990; Konen 1995; Clayton, Attig, and Mickelson 2001). In northern Europe and Scandinavia, the reported average is 30 × 13 m (Johnsson 1963, 1981; Rapp and Rudberg 1964; Svensson 1964, 1972, 1976; Ohrengren 1967; Gruhn and Bryan 1969; Aartholati 1970; Morgan 1971; Christensen 1974; Ghysels and Heyse 2006). Nonetheless, Clayton, Attig, and Mickelson (2001) reported fossil ice-wedge polygons from central and southeast Wisconsin that were up to 100 m in diameter, and Johnson (1990) described similar features from central Illinois that were up to 130 m across. Dylik (1966) reported active and inactive ice-wedge polygons from the Vorkuta and Bolshezyemielskay areas of Russia that were more than 950 m across. Recent imagery of the vicinity of Vorkuta, Russia, displays many examples of nonsorted polygons with long-axis lengths of 160 to 250 m.

The large mesh dimensions and irregular net form of the Saginaw patterned ground are consistent with permafrost cracking that 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; Mackay

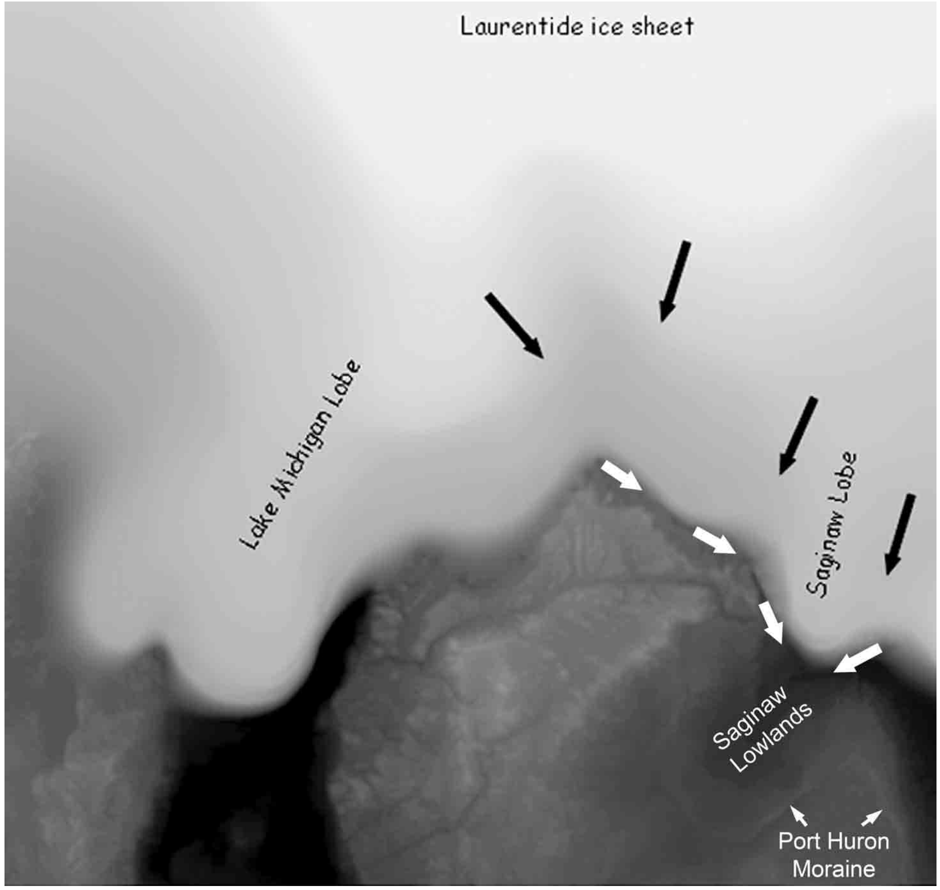

Figure 13. Inferred ice margin position at ~14.3 cal. ka. Note the lobate nature of the Laurentide ice sheet and the broad, interlobate sutures on the ice surface that collected and focused cold-air drainage toward the Saginaw Lowlands. The land surface is the digital elevation model from the U.S. Geological Survey National Elevation Dataset.

and Burn 2002) and is, therefore, also consistent with the late-glacial drainage history of the study area. The unusually large size of the polygons in the Saginaw Lowlands can also be explained by the relatively short period of time available for their formation (less than 500 years) and the relatively mild periglacial cold climate, as smaller polygons are usually the result of repetitive subdivisions of primary fissures during a protracted period of permafrost cracking associated with severe winter temperatures (Dostovalov and Popov 1966; Dylik 1966).

The sandy caps on the polygon interiors, whether thick or thin, could not have been derived from the silt loam material below via weathering or pedoturbation. Given the low slopes in the Saginaw Lowlands, the dominance of fine and very fine sand in the caps, the general lack of coarse fragments in the caps, and the presence of a large area of deep sandy soils 1 to 5 km to the southwest of our sites, it is likely that the sand cap on the polygon interiors is eolian. This scenario, however, is difficult to reconcile with the current sand distribution on the landscape—its patchiness, wide variation in thickness (0 to ~3 m), and its general absence from the lowest parts of the landscape (especially the polygon swales). Direct observations at our field sites and remote observations of agricultural fields attest to the patchiness of the sand, and the maximal sand cover thickness of 3 m stems from anecdotal evidence.

The absence of an overlying sand cap in the swale sites presents an interesting dilemma—one that we cannot fully explain. One possible explanation for the absence of sand within the swales involves the presence of active sand deposition only during a periglacial climate, when low-centered ice-wedge polygons were present and active in the landscape (Fortier and Allard 2004). Under this scenario, the low polygon centers could have been effective catchment basins for eolian sand, with some polygons amassing thicker accumulations of sand than others. Later, as temperatures increased and any existing ice wedges melted, the originally low polygon centers would have become topographically higher. The silty sediment adjacent to the ice wedges would have contemporaneously slumped into the voids left behind as the wedges melted, leading to topographically lower swales that were enriched with fine sediment, as we observed at our sites. Any existing sand caps in the polygon

Figure 14. The pit face at Site D, 1.1 m east of the ice-wedge cast described by Lusch (1982), showing what we interpret to be a thermokarst channel infilling.

centers would have been retained in place because of the initial depression and (perhaps) the increasing presence of vegetation.

A Probable Ice-Wedge Cast and Evidence of Regional Thermokarst

Black (1976) stated that ice-wedge casts are definitive evidence for fossil periglacial permafrost. In Illinois, Johnson (1990) used several occurrences of ice-wedge casts to link large areas of patterned ground, much like ours, to periglacial climates and the existence of permafrost. At Site D (Figure 4), we excavated, described, and sampled two exposures within 1.5 m of the original ditch face where Lusch (1982) had earlier observed and sampled a feature he interpreted as an ice-wedge cast (Figure 5). This is the only credible ice-wedge cast reported from anywhere in Michigan.

The easternmost pit face exhibited a distinct bowl-shaped body of sandy loam approximately 80 cm deep at its maximum extent and ~2.0 m wide at the surface. Its lower boundary was undulating but continuous across the pit face, retaining all of the sandy sediment above it, with no sandy outliers in the silty matrix below and no silty outliers within the sandy loam body. The feature exhibited an abrupt lower boundary to dense, subangular blocky and platy, strongly calcareous silt loam material, which we interpret as dense till. In contrast, the bowl-shaped sandy loam deposit is dominated by medium sands. The lowermost sediments in the bowl-shaped feature, especially near the edges, were slightly better sorted than most of the sandy material above.

The second, excavated face—only about 1.1 m east of the ice-wedge cast described by Lusch (1982)—exhibited a similar bowl-shaped sandy loam deposit but with a much more irregular lower outline (Figure 14). Bulbous protrusions of sandy material at a variety of angles into the silty host material below were common here; when the face was cleaned backward these outlines ebbed or grew, reflecting their complex three-dimensional shapes. Small pebbles (1–6 cm in diameter) were situated at the contact between the sandy infill and the silty substrate, but did not exhibit any apparent orientation. Pebbles like these have been noted elsewhere at the edges of presumed ice-wedge casts (Morgan 1972).

The form and sedimentology of the ice-wedge cast described by Lusch (1982) is convincing evidence for the presence of permafrost in this area at some time in the past. The associated bowl-shaped deposits that we excavated just to the east of this ice-wedge cast, however, are not ice-wedge casts, although they appear to be laterally continuous with the ice-wedge cast (the landowners' concern over ditch-edge erosion precluded us from excavating all the way to the ditch face). We suggest that these bowl-shaped sandy loam deposits are thermokarst deposits—the remnants of thermally degraded ice wedges.

The impaired drainage of the silt loam till that dominates the Saginaw Lowlands would almost certainly have promoted ice-rich permafrost under the right microclimatic conditions. Czudek and Demek (1970) reported that perennially frozen loam soils under saturated conditions can contain 30 to 80 percent segregated or vein ice. The amount of ground ice in saturated permafrost usually exceeds the liquid limit of the regolith, making it prone to liquefaction on thaw (French 1975). The liquid limits of the parent materials of the four soil series most commonly associated with the Saginaw patterned ground (Capac, Londo, Parkhill, and Tappan) range from 20 to 45 percent (NRCS 2007).

In the initial phase of this thermokarst development, high-centered polygons probably formed as the reticulate network of ice wedges began to thaw. These thermokarst troughs grew successively deeper as the thermal erosion of the wedge ice continued. The polygon centers probably retained their initial elevations and flat surfaces until the encircling troughs reached a depth of about 1 m—an amount of relief sufficient to induce slumpage or flowage of the unstable active layer into the troughs, which transformed the originally narrow thermokarst troughs into broader channel forms with irregular bottom profiles. In the final phase, a few of the deeper troughs became the depositional sites for eolian sands that were blowing across this low-relief terrain that initially had very little large-stature vegetation growing on it.

Conclusions

Based on aerial photography and soils data, and working within a distinctly geographic paradigm, we described and mapped widespread areas of patterned ground in the Saginaw Lowlands of east central Michigan. Although more study is required before this interpretation can be confirmed, we ascribe these patterns to thermal-contraction cracking of widespread, but short-lived, permafrost during the Late Wisconsin. Within the Lowlands, patterned ground is found in three main clusters, two of which are bracketed by former glacial shorelines, suggesting that the formation of these features dates to a time immediately after the uppermost shoreline was active; the patterns could not have formed under deep water. Based on the distribution of the patterned ground between the shorelines of glacial Lakes Warren (14,800 cal. years ago) and Elkton (14,300 cal. years ago), thermal-contraction cracking of the permafrost might have only lasted for about five centuries.

Most of the patterned ground has developed (or at least has been preferentially preserved) in areas of somewhat poorly and poorly drained silt loam and loam soils where slopes are generally less than 3 percent. Sandier and drier areas tend not to have patterned ground, although at several of our study sites polygon interiors were mantled with up to 80 cm of fine sand. The origin of this sand cover is unclear, but it might be eolian. We also described a bowl-shaped sandy loam deposit, set within an interpolygon swale area, which we interpret as a thermokarst channel infilling that follows the trace of a former ice wedge.

If our thermal-contraction cracking genesis is correct, the subtle morphology and sedimentological characteristics of the patterned ground in the Saginaw Lowlands suggest that, rather than ice-wedge replacement, thermokarst development coupled with solifluction were the dominant geomorphic processes associated with the degradation of the Late Wisconsin permafrost in the study area.

Acknowledgments

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Correspondence: Department of Geography, Michigan State University, East Lansing, MI 48824, e-mail: lusch@msu.edu (Lusch); soils@msu.edu (Schaetzl); blumerbr@msu.edu (Blumer); hobbstre@msu.edu (Hobbs); archerj1@msu.edu (Archer); freela10@msu.edu (Holmstadt); Department of Geography, University of Wisconsin–Madison, Madison, WI 53706, e-mail: kstanley@wisc.edu (Stanley); Department of Geological Sciences, Michigan State University, East Lansing, MI 48824, e-mail: kendal30@msu.edu (Kendall); rvd@msu.edu (Van Dam); maychri1@msu.edu (May); Department of Geography & Geology, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark, e-mail: asn@geogr.ku.dk (Nielsen).