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Mapping the physiography of Michigan with GIS

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Abstract: We present a new physiographic map of Michigan, that is also available interactively, online. Only four, small-scale physiographic maps of Michigan had been previously published. Our mapping project made use of a wide variety of spatial data, in a GIS environment, to visualize and delineate the physical landscape in more detail than has been done previously. We also examined many of the unit boundaries in the field, using a GIS running on a GPS-enabled laptop. Unlike previous physiographic maps, the online version of the map enables users to query the criteria used to define each of the 224 boundaries of its 10 major and 91 minor physiographic units. The interactive nature of the online version of the map is a unique enhancement to physiographic maps and mapping. Our study also provides data on the number and types of criteria used to define each of the 224 unit boundaries within the map. Most of our unit boundaries are based on data derived from 10-m raster elevation data and NRCS soils data, e.g., relief, soil wetness, escarpments, landscape fabric, and parent material characteristics. Data gleaned from NRCS SSURGO county-scale soil maps were a strength of the project. [Key words: Michigan, physiography, landforms, soils, GIS, mapping]

Introduction

Physiographic maps are cartographic representations of the broad-scale physical regions of an area, often based on terrain, sediment and rock types, and geologic structure and history (Salisbury, 1909; Raisz, 1931). Their purpose is to delineate physical regions that have internal uniformity with respect to one or more environmental attributes, and which are clearly different from those regions surrounding it.

Physiographic maps may be considered a type of landform or land-type map, and yet these maps are subtly different in their emphases. Landform/geomorphic maps focus more on topography and relief, i.e., the relative locations of hills and valleys, lowlands and uplands (Fenneman, 1917; Hammond, 1963, Pike & Thelin 1990). Genetic processes are often inferred from landform maps, e.g., Quaternary geology, loess thickness, or areas of sand dune activity (Zelčs and Dreimanis, 1997: Wang et al., 2010). Boundaries on landform maps can usually be determined using surface elevation data alone, as in a DEM, by employing some sort of rule-based, object-oriented mapping technique (Brown et al., 1998; Asselen and Seijmonsbergen, 2006; Arrell et al., 2007; Camargo et al., 2009; Saha et al., 2011). Such approaches allow for the rapid collection, analysis, and mapping of data in a generally unbiased and non-subjective manner. However, these methods can be expensive and many result

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in, as Stepinski and Bagaria (2009, 733) stated, "pixel-based maps that do not quite match an appearance and usability of manually drawn maps."

Physiographic maps and mapping are important because they delineate areas that are relatively uniform with respect to key physical attributes. Land-use decisions, as determined for these regions, may—or perhaps should—have shared goals, approaches, and limitations. Perhaps not coincidentally, an increasing number of U.S. states recently have produced physiographic maps, often posting them online (Table 1). In most cases, these maps result from efforts by a state geological survey, e.g., Wahrhaftig (1965) or Gray (2000), or similar governmental entity, e.g., Robitaille and Saucier (1996). This trend suggests that (1) the increasing volume and quality of available spatial data are facilitating such mapping efforts, and (2) the utility of these maps is increasingly becoming recognized, particularly with regard to regional land-use planning, interpretation of landscape evolution, and the effects of physiography on other aspects of the surficial and ecological environment (Good et al., 1993; Steenfelt, 1993; Pachauri et al., 1998; Martin-Duque et al., 2003; Kilic et al., 2005, Johansen et al., 2007; Daly et al., 2008; Fearer et al., 2008; Johnson and Fecko, 2008; Gawde et al., 2009; Stepinski and Bagaria, 2009).

Table 1. A Selection of Current, Statewide U.S. Physiographic Maps

State	URL, or published source	Scale[a]	Publ. Date
AL	http://alabamamaps.ua.edu/contemporarymaps/alabama/physical/al_physio.jpg	1:2,290,000	?
AR	http://www.arizonaedventures.com/reference-guide/arizona-physiographic-regions/	1:2,700,000	?
AZ	http://www.arizonaedventures.com/reference-guide/arizona-physiographic-regions/	1:2,632,000	?
CA	http://geologycafe.com/california/maps/provinces3.htm	1:4,224,000	?
GA	Clark and Zisa (1976)	1:2,400,000	1976
IL	Leighton et al. (1948)	1:3,168,000	1948
IN	Gray (2000)	1:660,000	2000
KS	http://www.kgs.ku.edu/Physio/physio.html	1:4,684,000	?
KY	McGrain (1983)	1:3,168,000	1983
LA	Yodis and Colten (2003)	1:3,168,000	2003
MD	http://www.mgs.md.gov/coastal/maps/physio.html	1:193,000	2008
ME	Toppan (1935)	1:8,000,000	1935
MI	Veatch (1930)	1:4,800,000	1930
MI	Sommers (1977)	1:4,236,000	1977
MI	Schaetzl et al. (2009), Plate 8	1:2,500,000	2009
NJ	http://users.rowan.edu/~hasse/enri_html/report_html/chapters/007.html	1:2,625,000	?
OH	http://www.governorsresidence.ohio.gov/garden/physiographic.aspx	1:3,260,000	?
OH	Brockman (1998)	1:660,000	1998
PA	http://www.dcnr.state.pa.us/topogeo/maps/map13f.pdf	1:1,600,000	2000
SC	http://www.hiltonpond.org/PiedmontMain.html	1:6,626,000	?
SD	Johnson et al. (1995)	1:4,286,000	1995
TX	http://www.beg.utexas.edu/UTopia/images/pagesizemaps/physiography.pdf	1:3,846,000	1996
VA	http://web.wm.edu/geology/virginia/provinces/pdf/va_physiography.pdf	1:3,333,000	1999
VT	http://academics.smcvt.edu/vtgeographic/textbook/physiographic/physiographic_regions_of_vermont.htm	1:1,000,000	1986
WI	Durand (1933)		1933

[a] Map scales are estimated, if not expressly stated on the map.

Michigan's geological survey has not yet published a physiographic map. Indeed, three of the four existing physiographic maps of Michigan appear only as small-scale, inset maps in books. And these maps were not focused efforts to map physiography per se (Veatch 1953, Sommers 1977, Schaetzl et al. 2009). The one exception is a small-scale map produced by J. O. Veatch in 1930 as part of an article mainly intended to show that physiographic mapping was then actually possible. While these efforts were laudable for their time, especially given the available data and mapping technologies, the map we present is an advance over these previous efforts, both in methods and results. Our purpose is to present a new, large-scale physiographic map of Michigan. In so doing, we demonstrate a mapping (and online presentation) approach using GIS and spatial data that others can pattern. Modifying this approach to fit the data available can also be easily done for other applications. Equally important, however, we draw upon innovative, student-based research and mapping methods, and we utilize many recently obtained data sources to develop this map. The role of GIS in delineating physiographic regions exemplifies contemporary progress in physiographic mapping, as data quality and quantity continue to improve. Perhaps never before have so many detailed and unique datasets been combined to create a physiographic map. Because the map and its online version (http://www.physiomap.msu.edu/) were created as a classroom project, we believe that our methods have pedagogic as well as scientific applicability. That is, we applied a student-based approach to boundary delineation and decision-making, guided by a rich suite of GIS data layers.

Data and methods

GIS/Mapping and Data

This physiographic mapping project started as seminars in geography, at Michigan State University, instructed by Schaetzl and Lusch. Mapping efforts run as a part of seminars have been successful pedagogical pairings for us in the past (Arbogast et al., 1997; Schaetzl et al., 2002; Hupy et al., 2005; Lusch et al., 2009; Vader et al., 2012).

The instructors and eight students first assembled a diverse set of spatial data within a GIS (Table 2). Many of these data layers exist on the State of Michigan's Geographic Data Library web site (http://www.mcgi.state.mi.us/mgdl/). The Remote Sensing and GIS Research and Outreach Services unit at Michigan State University (a component of the Department of Geography) also provided several key, internally-housed, datasets. Preexisting geomorphic and physiographic maps of the state were scanned, georectified, projected, and entered into the same GIS project. In ArcGIS 9.3 (© ESRI, Redlands, CA), we were able to view several data layers simultaneously by making various layers semi-transparent. Use of these GIS data layers enabled us to visualize the physical landscape in ways that could not have been done previously, thereby making our mapping effort richer and more detailed. This method of GIS-assisted landscape visualization is recommended for similar mapping efforts in the future. In traditional physiographic mapping, the information supplied from these *additional types of data*, e.g., soils, hydrology, bedrock lithology and regolith thickness, is often just as important to the delineation of regional boundaries as are topographic data. Thus, we argue that physiographic maps will better reflect the physical landscape if they include more than just topographic information.

Among the numerous datasets assembled for the project (Table 2), we accessed a seamless mosaic of Digital Raster Graphics (DGRs: scanned 7.5-minute topographic maps) for the entire state. Our DEM and hillshade rasters were at 10-m resolution (USGS, 2009). From the digital elevation data, we derived a measure of local relief using neighborhood analysis to

Table 2. Sources of Geographic Data for this Study

Data layer/type[a]	Scale/Resolution[b]	Source
Preexisting maps		
Physical regions	1:250,000	Veatch (1930)
Natural land divisions	1:1,000,000	Veatch (1953)
Physiographic regions	1:3,800,000	Sommers (1977)
Physiographic regions	1:2,500,000	Schaetzl et al. (2009), Plate 8
Landforms	1:2,700,000	Raisz and Mills (1968)
Quaternary geology	1:500,000	Farrand and Bell (1982)
NE Lower Peninsula landforms	1:650,000	Burgis (1977)
Western Upper Peninsula landforms	Digital only	http://www.mi.nrcs.usda.gov/soils.html
NW Lower Peninsula landforms	Digital only	http://www.mi.nrcs.usda.gov/soils.html
Western Upper Peninsula surficial geology	1:250,000	Peterson (1985)
Ecoregions	1:100,000	Albert (1995)
Natural vegetation at time of GLO surveys	1:100,000	Comer et al. (1995)
Major Land Resource Areas	Digital only	http://datagateway.nrcs.usda.gov/ or http://soils.usda.gov/survey/geography/mlra/index.html USDA, NRCS (2006)
Northern Lower Peninsula landscape linearity	1:1,400,000	Schaetzl (2001)
Topographic maps (as DRGs)	1:24,000	US Geological Survey (various dates)
Digital databases		
Elevations	10-m raster	USGS (2009)
Elevation difference for all points within a 250-m radius (calculated from DEM)	30-m raster	USGS (2009)
Anderson Level I land cover types (2000) - Level I	30-m raster	http://www.mcgi.state.mi.us/mgdl/
Anderson Level I and II cover types (2006) – Level I and II	30-m raster	NOAA Coastal Services Center (2008) http://www.csc.noaa.gov/digitalcoast/data/ccapregional/
Agricultural crops	56-m raster	USDA, National Agricultural Statistics Service (2007) http://datagateway.nrcs.usda.gov/
Bedrock geology	Sources at 1:63,360; Compiled at 1:500,000	(Milstein, 1987; Reed and Daniels, 1987) http://www.mcgi.state.mi.us/mgdl/
Bedrock surface elevation	500-m raster	RS&GIS, Michigan State University (Lusch et al., 2005)
Glacial sediment thickness above bedrock surface	500-m raster	RS&GIS, Michigan State University (Lusch et al., 2005)
Depth to water table	30-m raster	RS&GIS, Michigan State University (Lusch et al., 2005)
Surface hydrology	1:100,000	USGS (2007) http://nhd.usgs.gov/
Glacial landsystems	1:500,000	(Lusch et al. (2005); Schaetzl et al. (2009a; Plate 10) http://www.mcgi.state.mi.us/mgdl/

(*Continued*)

Table 2. (*Continued*).

Data layer/type[a]	Scale/Resolution[b]	Source
Surficial sediment/soil data, derived from NRCS maps		
Parent material as determined from Official Soil Series Descriptions	1:15,840	NRCS Soil Survey Geographic (SSURGO) Database http://soildatamart.nrcs.usda.gov/
Texture of uppermost mineral horizon	1:15,840	NRCS Soil Survey Geographic (SSURGO) Database http://soildatamart.nrcs.usda.gov/
Texture of lowermost mineral horizon	1:15,840	NRCS Soil Survey Geographic (SSURGO) Database http://soildatamart.nrcs.usda.gov/
Parent material graveliness	1:15,840	NRCS Soil Survey Geographic (SSURGO) Database http://soildatamart.nrcs.usda.gov/
Natural Soil Drainage Index[c]	1:15,840	NRCS Soil Survey Geographic (SSURGO) Database, in conjunction with Schaetzl et al. (2009).
Derived paleo-lake level shorelines		
Glacial Lake Algonquin, highest and lowest shorelines[d]	1:1,400,000	Schaetzl et al. (2002); S. Drzyzga, pers. comm. (2009)
Glacial Lake Saginaw, highest shoreline[4]	1:100,000	Lusch et al. (2009)
Glacial Lake Chicago, highest shoreline	Digital only	Derived in-house

[a]Statewide coverage is assumed, unless otherwise noted.
[b]Approximate scale, if not explicitly stated on the original.
[c]Ordinal ranking of natural soil wetness classes, 0–99.
[d]Adjusted across its extent, for isostatic rebound.

calculate the elevation range in a 250-m circle for each output cell. The use of similar local relief measures as a mean of delineating regions has been successfully applied in other glacial landscapes (Stoelting, 1989).

Surficial and bedrock geology maps were available as digital shapefiles from the Michigan Geographic Data Library. County-scale (1:63,360) bedrock geology maps had been digitized in the late 1980s by the Michigan Department of Natural Resources and compiled into a statewide map, subsequently published on paper (Milstein, 1987; Reed and Daniels, 1987). The 1:500,000-scale surficial/Quaternary deposits maps by Farrand and Bell (1982a; 1982b), based in large part on the surface formations map by Martin (1955; 1957), had been digitized by the Michigan Natural Features Inventory. A glacial landsystems map, compiled by combining the Farrand and Bell line work and the NRCS STATSGO soil texture data (1:250,000) was also used (Lusch et al., 2005; see also Plate 10 in Schaetzl et al., 2009). Like much of our data, both the Quaternary geology map and the glacial landsystems maps are available from the Michigan Geographic Data Library.

Existing landform and geomorphic maps of within-state regions also were highly useful, particularly because they were created at larger scales than were maps of statewide extent. We utilized a USGS map of the surficial geology of the western Upper Peninsula (Peterson, 1985), which was especially helpful because physiographic mapping in that part of Michigan is complicated by the influence of near-surface bedrock, the impact of which on surface landforms is difficult to determine. The NRCS has published two digital landform maps – one for the entire Upper Peninsula and one for the northern Lower Peninsula. These maps are quite detailed. We also made use of landform maps of the northeastern Lower Peninsula (Burgis,

1977) and the northwestern Lower Peninsula (Blewett, 1990), both developed in conjunction with doctoral dissertations.

We added a bedrock surface and a glacial thickness map, both newly revised by Lusch, incorporating over 270,000 point observations of the bedrock surface elevation (149,427 points in the Lower Peninsula and 124,570 points in the Upper Peninsula). For each of these points (mainly oil, gas and water well logs), a "top of bedrock elevation" field was calculated by subtracting the depth to bedrock from the surface elevation (USGS National Elevation Dataset DEM). Point values for the top-of-bedrock elevation and the depth to bedrock were independently interpolated statewide by ordinary kriging onto an output grid with 500 x 500-m cells. Both of these initial output surfaces were subsequently smoothed with a 3 x 3 averaging filter to produce the final bedrock surface and glacial thickness maps (http://gwmap.rsgis.msu.edu/).

The 2007 Cropland Data Layer (CDL) (USDA, 2007) for the state was produced by a partnership between the Land Policy Institute at MSU and the USDA, National Agricultural Statistics Service. The 2007 CDL for Michigan has a ground resolution of 56 m and was classified from ResourceSat-1 Advanced Wide Field Sensor satellite imagery that had been collected during the 2007 growing season. Ancillary classification inputs included the USGS National Elevation Dataset, the USGS National Land Cover Dataset 2001, and the 250-m, 16-day Normalized Difference Vegetation Index composites from the NASA MODIS program. Agricultural training and validation data were derived from the Farm Service Agency Common Land Unit Program. Twenty-seven crops were mapped in this layer, including Michigan's most common crops: corn, soybeans, and winter wheat. The 2007 CDL for Michigan also mapped six non-crop covers: woodland, wetland, developed, shrubland, barren and water. In addition, our mapping project used two 30-m land-cover classifications from ca. 2000 (Michigan Department of Natural Resources. 2003), and ca. 2006 (NOAA, 2008), both of which contained natural land-cover attributes to Anderson Levels II and III, derived from Landsat imagery.

Our soils datasets were a decided strength of the project; soils data are increasingly the primary input to projects that map areas of similar physiography, geomorphic history, and character (Robinove, 1979; Millar, 2004; Brye, 2009). NRCS SSURGO soils data, derived from large-scale county soil surveys, were downloaded from the NRCS Soil Data Mart web site (http://soildatamart.nrcs.usda.gov/). The 83 county soil surveys were merged into a statewide vector file and subsequently converted to a 30-m raster grid. The statewide soils grid file was only 2.21 GB (uncompressed) in size, considerably smaller than the parent vector file, making it much easier to manipulate in a GIS. Next, we developed a unique and highly useful anthology of attributes for each soil series in the statewide grid file—data that were directly related to surficial deposits, but at a much finer scale than is normally attainable from statewide surficial geology maps. We coded as many of the soil series as possible to a parent material category by first downloading the official series description from the NRCS web site (http://soils.usda.gov/technical/classification/osd/index.html) and noting the parent material that is written into the series description. The parent material description was copied verbatim, enabling us to code most of the series to one of several classes: till, outwash and glaciofluvial sediment, loess, lacustrine sediment, dune sand, and a few other, minor categories. For soils with loess listed as the upper parent material, the underlying sediment was also noted. Eventually, we were able to code 439 of the 624 mapped soil series in Michigan to a parent material class. A parent material map of such detail is normally unavailable; it must be derived from SSURGO data. We envision that this type of data coding will be increasingly utilized in future research. In a similar manner, we coded each series to the texture of the surface mineral (usually A) horizon, as well as its parent material (lowest horizon). We also noted when the texture modifier on the lowest horizon contained the words "gravelly," cobbly," or "stony," allowing us to compile a data layer for soils that contain significant amounts of coarse fragments in their parent materials. In the end, we had four large-scale datasets, each derived from the NRCS SSURGO soils data: parent material type, upper solum texture, lower solum texture, and graveliness. Finally, we found great utility in the Drainage Index (DI) of Schaetzl et al., (2009), a measure of the long-term, natural wetness of soils. We used the join file on the DI web site (http://www.drainageindex.msu.edu/) to assign each soil series in Michigan to its appropriate natural wetness (DI) value; the result was a map of landscape wetness.

We recognize that biotic communities are a function of soils, climate, hydrologic resources, and other physical factors that comprise a physiographic region (Omernik, 1987). Thus, our two datasets of this nature—presettlement vegetation (Comer et al., 1995; http://web4.msue.msu.edu/mnfi/data/veg1800.cfm) and contemporary ecoregions (Albert, 1995)—were particularly useful for delineating regions, as well as for characterizing them.

Several existing maps and databases about the various proglacial lakes in Michigan were helpful for delineating the boundaries of glacial lake plains. We used rebound-adjusted DEMs, presented in Schaetzl et al. (2002) and refined by Drzyzga et al. (2011), as guides for the uppermost and lowermost shorelines of Glacial Lake Algonquin in the northern Lower and eastern Upper Peninsulas. Although these DEMs allowed us to infer the approximate location of the shoreline, we consistently deferred to wave-cut bluffs and other features, where present, to refine the shoreline location. Nonetheless, the accuracy of the DEMs was excellent. We also used a polyline shapefile of the highest paleolake shorelines in the Saginaw Lowlands that had been digitized earlier by Lusch et al. (2009). Lastly, we compiled a shapefile of the uppermost shoreline(s) of Glacial Lake Chicago. To do this, we referred to the shorelines mapped by Farrand and Bell (1982b), but our digitizing was mainly guided by our own interpretations of wave-cut bluffs and soil texture/parent material breaks on the landscape.

The Classroom Mapping Effort

After the assembly of these various datasets into a GIS framework, the class was divided into four groups, with Schaetzl working alone as a fifth "group." Our mapping effort used the most recent physiographic map of the state (Schaetzl et al., 2009; Plate 8) as a guide, while working to improve upon it, given the larger scale and more detailed datasets to which we now had access. Knowing that our end product would be a much larger-scale map than that of Schaetzl et al. (2009), we were not constrained by cartographic line generalization principles as we digitized our region boundaries.

After a series of class lectures that provided detailed background on the geomorphic history and physiography of the state, the students entered into an independent learning/mapping phase, manually inspecting data layers in a GIS and repeatedly drawing, redrawing, and refining lines and region boundaries. In the end, we judged that our map was, although more subjective, more accurate and more complete, with greater intra-regional homogeneity, than could have been achieved using more automated, "objective" or object-oriented approaches, e.g., Dikau et al. (1995), Brown et al. (1998), Burrough et al. (2000), Adediran et al. (2004), Dragut and Blaschke (2006), Iwahashi and Pike (2007), which often rely mainly or exclusively on topographic data and a programmed GIS/taxonomic algorithm.

Initially, the students presented their "first cut" boundaries and regions to the class, for criticism and feedback. Projected presentations were made from laptop computers running ArcGIS. In this way, each boundary and region could be viewed by the class as a whole, while different data layers were turned on and off, and the regions examined at various display scales. This effort served two purposes: (1) feedback provided by the class helped each group refine, adjust, and improve their region boundaries, sometimes leading to the creation of new regions or the merging of regions, and (2) it provided valuable opportunities for oral presentation, much like a research "defense" in front of an audience of peers and supervisors. Most of the regions and their boundaries were presented to the class two to four times, generating abundant feedback and resulting in everything from large changes in some map boundaries to complete affirmation and acceptance of other proposed map regions.

Field Methods/Ground Truthing

After the class had gone through several iterations of boundary delineations, and consensus was reached that our boundaries and regions were reasonably well defined, we entered into a field-checking (ground truth) mode. Our goal was to examine the internal homogeneity of our regions (as observed along our lines of traverse) and to field-check the boundaries. To do this, we needed to drive into and through as many of our delineated regions as time allowed. We

Fig. 1. The major physiographic regions of Michigan.

were assisted in this effort by a laptop computer equipped with an internal GPS, displaying our GIS project, e.g., Whitmeyer et al., (2010). Thus, we were able to view our progress as we travelled through each region, while at the same time turning various data layers on and off to help connect landscape characteristics (as viewed from the vehicle windows) with the GIS data viewed on the computer. In all, we travelled through 56 of our 91 regions, and crossed regional boundaries at 111 different places, over the course of six days. This phase of the project was highly successful; it helped us to redefine or refine many of our boundaries and regions, and gave the group a much better mental map of the character of the regions that we had been studying and mapping.

Results And Discussion

Overview of the Map

The map has two levels or categories. At the aggregated level there are ten major physiographic regions (Fig. 1). At level two, we delineated 91 physiographic regions (Fig. 2). Most previous small-scale physiographic maps show regions similar to our major regions. Few such maps are created at a level of detail that is equivalent to our minor (Level 2) region subdivisions. As Figure 3 indicates, the mean size of our *major* regions is typical of regions on

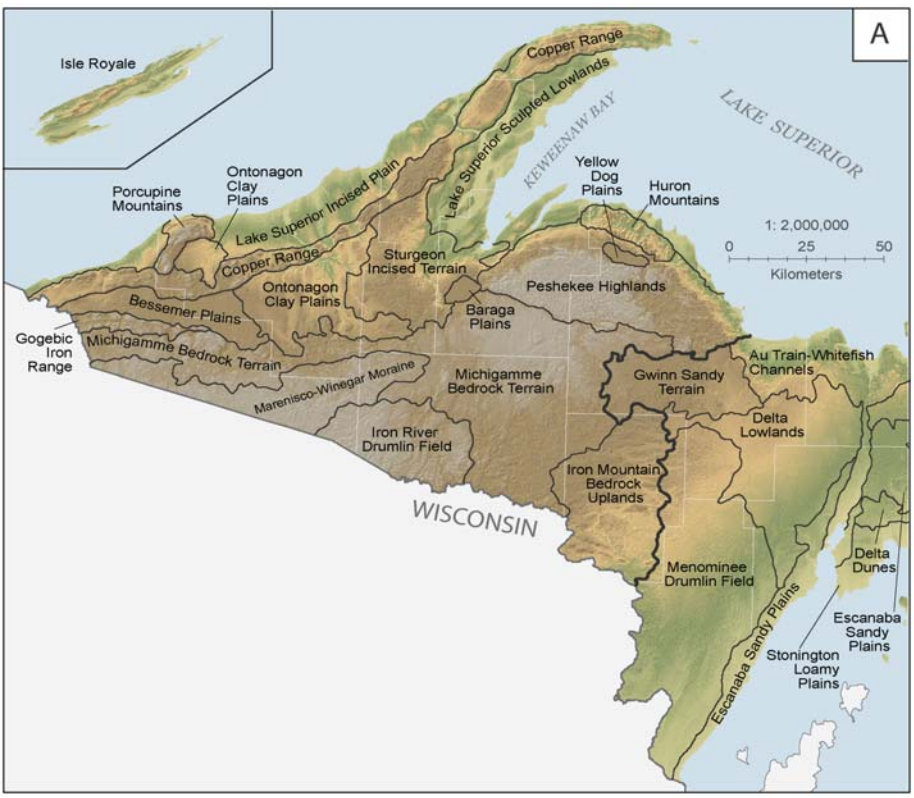

Fig. 2. Our physiographic map of the State of Michigan, presented in three segments: (A) the western Upper Peninsula, (B) the eastern Upper and northern Lower Peninsulas, and (C) the southern Lower Peninsula

Fig. 2. continued

many other state physiographic maps. Alternatively, only the state physiographic map of Maryland has regions that are generally smaller than our minor regions, with a mean size of 1665 km^2/region (Fig. 3). Thus, we believe that the map presented here is a unique cartographic, methodological, and physical geographic contribution to the literature, and that the additional detail will make it more useful in on-the-ground applications. Our physiographic map is shown in Figures 2A, 2B, and 2C, subdivided into three parts so that each sub-region can be represented at a large enough scale to sufficiently show ample detail.

Fig. 2. continued

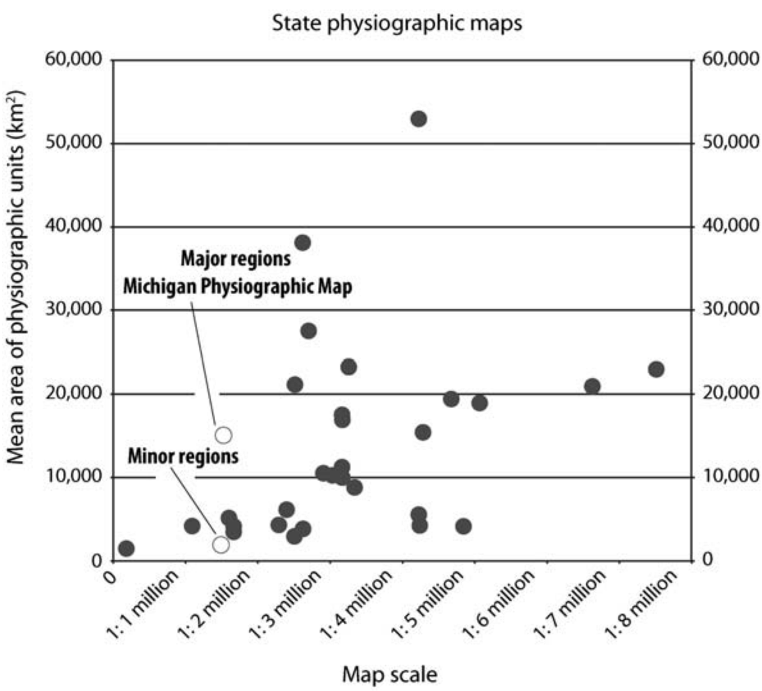

Fig. 3. Scatterplot showing the mean sizes of regions on other state physiographic maps, as a function of map scale.

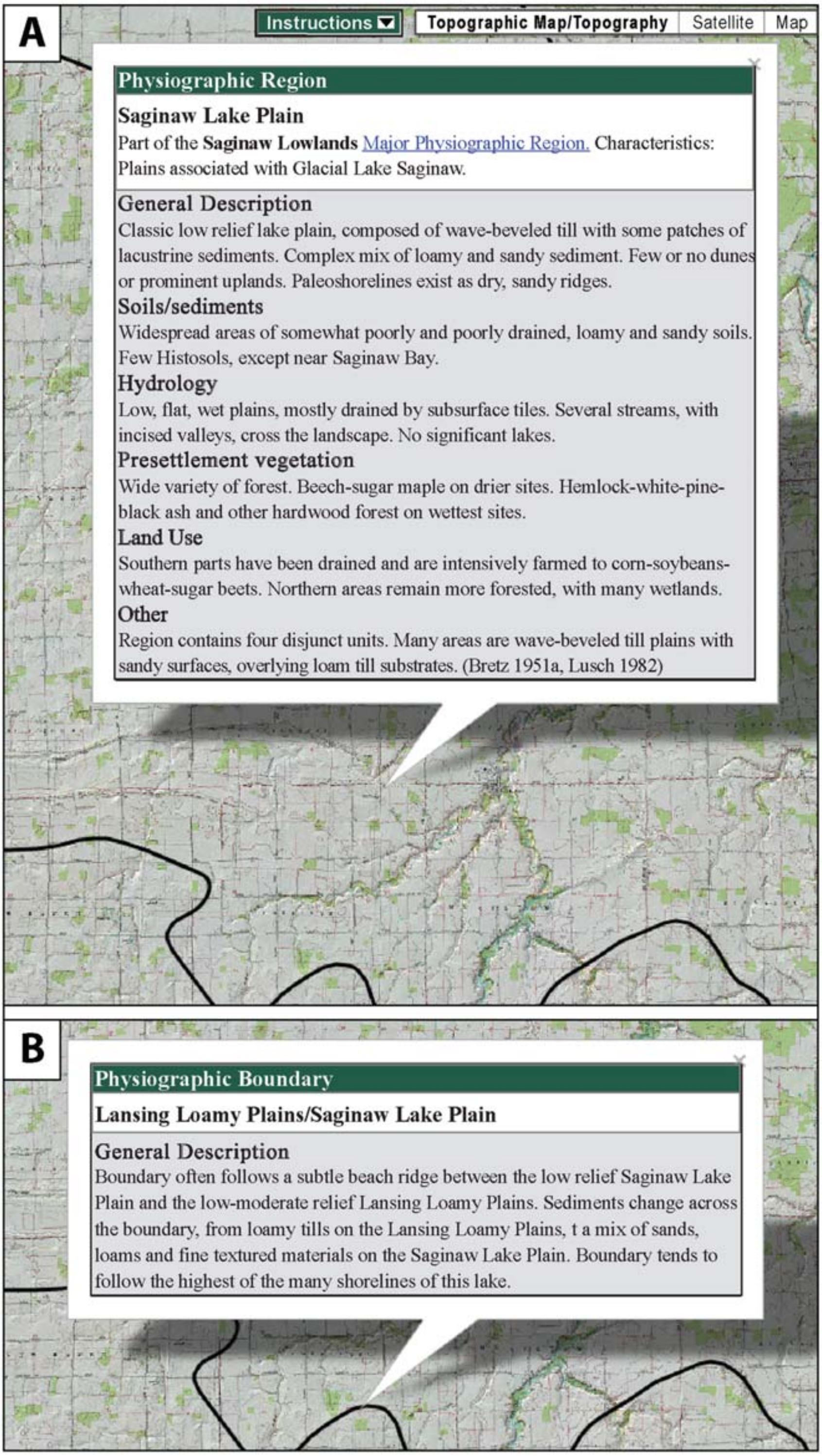

Fig. 4. Screenshots of the online, interactive map, showing (A) the pop-up window that appears after the user clicks within a region, and (B) the pop-up window that appears after the user clicks on a region boundary.

Equally important to this mapping effort is our online, interactive map, available at http://www.physiomap.msu.edu/. This map is not subdivided; it exists as a seamless, statewide digital map. In addition to the normal zoom and pan features, this map has some unique interactive features, e.g., when a user rolls their mouse over a region and clicks, a pop-up window reveals information about the region's topography and relief, soils, hydrology, and paleovegetation (Fig. 4), generally as listed in Appendix 1. More importantly, by clicking on any of the boundary lines, the online map also provides information about the criteria and logic we used to define that particular boundary segment, e.g., changes in topography, soils, or some other physical factor. We believe that ours is the first such interactive physiographic map, and also the first map of its kind that provides clear indications of the criteria used to delineate regional boundaries.

Our regional naming protocols followed these two general rules: (1) if a region had been named previously, or had a name that was in common use locally, we adopted that name (although we may have altered its boundaries from previously published maps), or (2) if a new region was recognized, we derived a name based on a local place. We strove for inter-regional consistency in our terminology, e.g., uplands, lowlands, plains, hills, as well as how we described the overall relief of the region (Appendix 1). Similarly, we avoided use of genetic names, unless their physical/geomorphic genesis was clear and undisputed. For example, we felt justified in using genetic names for some of the prominent drumlin fields, long-established moraines, deltas, lake plains and dune fields. However, when the genesis of the region was either complex, multi-faceted or unclear, we defaulted to more generic names, e.g., plains, hills, terrain, channels, mountains, or uplands.

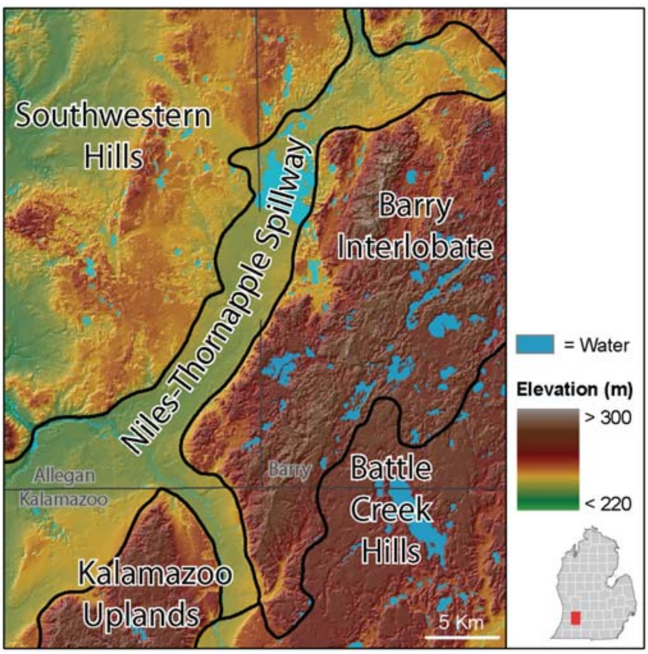

Fig. 5. Regional boundaries in southwestern Lower Michigan, illustrating the Niles-Thornapple Spillway, where it meets the sandy, morainic uplands of the Allegan Hills and the Barry Interlobate. As in other maps of this type, the map shows a semi-transparent GIS layer on top of a hillshade, along with the county boundaries. In this case, a color elevation ramp is shown overlying the hillshade layer. Note the abrupt, erosional, topographic escarpment that separates these regions.

Unlike similar mapping efforts that have relied mainly on elements of topography (e.g., elevation, surface roughness, aspect, slope gradient and curvature), and/or soils as the primary inputs (e.g., Miliaresis and Argialas, 1999; Sathymoorthy et al., 2007; Zhalnin and Parker, 2009), our map incorporates topography and elevation as only two of several inputs, or data layers. We found that local relief, soil wetness, as indicated by the Drainage Index of Schaetzl et al. (2009), and especially soil parent material and soil texture, all were highly useful in defining regional boundaries. Many boundaries followed clear and unmistakable breaks in slope, often at the edges of lake plains, along the margins of meltwater channels, and at the footslopes of constructional landforms such as moraines. Boundary placements for a few regions were guided by the depth to bedrock and drift thickness data. Likewise, we found that land cover and crop layers were most helpful in verifying boundaries, as they often are directly a function of the region's underlying biophysical characteristics (Hill and Mawby 1954).

Types of Regional Boundaries

This map makes a significant contribution to mapping science in the area of boundary selection criteria. Not only does our online map allow the user to identify the main criteria upon which each boundary was determined, but it is also noteworthy that many of the map's boundaries are defined by a multitude of criteria. Many of the 224 region boundaries are mapped at locations where several physical parameters all change simultaneously (Appendix 1). We are unaware of any previous physiographic map provides detailed, spatially specific information about the criteria used to delineate its boundaries. The following text lists the many types of boundaries on the map, although the reader is cautioned that most boundaries on our map are not determined by only one criterion.

1. Topographic escarpments. In areas of high relief, such as Alaska, most physiographic boundaries are drawn along topographic breaks (Wahrhaftig, 1965). In a state like Michigan, where local relief is much lower, these types of boundaries should, theoretically, be less common. Nonetheless, many regional boundaries on our map follow the edge of a topographic escarpment, e.g., an erosional feature associated with glacial meltwater, a wave-cut bluff at the margin of a lake plain, or a bedrock cuesta. This type of regional boundary generally was the easiest to delineate. Figure 5 illustrates the glacial meltwater channel that forms the core of the Niles-Thornapple Spillway, where it meets the sandy, morainic uplands of the Allegan Hills and the Barry Interlobate. This figure is an example of a boundary dictated by sharp topographic changes. Here, several boundaries are shown, all of which are defined largely on topography. The Yellow Dog Plains is an outwash plain defined on the south by the abrupt bedrock escarpment that leads to the higher elevation Peshekee Highlands (Fig. 6). On its northern margin, the Yellow Dog Plains is defined by a gullied erosional escarpment cut into the outwash sand. The high elevation, high relief, Huron Mountains also are shown in Figure 6; their southern boundary follows the bases of large bedrock knobs.

2. Landscape fabric. Regional boundaries can occur where the overall texture of the physical landscape changes. This type of "landscape fabric" change has been shown to be an important indicator of glacial history (Schaetzl, 2001). It can manifest itself as changes in the strength of lineation of surface features, e.g., drumlins (Fig. 7), or as differences in overall landscape pattern and surface morphology, e.g., from a densely kettled landscape to one with fewer depressions (Fig. 8), or from a flat, nearly featureless plain to one with numerous sand dunes. In a state where the landscape is geologically young and largely composed of constructional glacial and eolian landforms, different landscape fabrics are often associated with

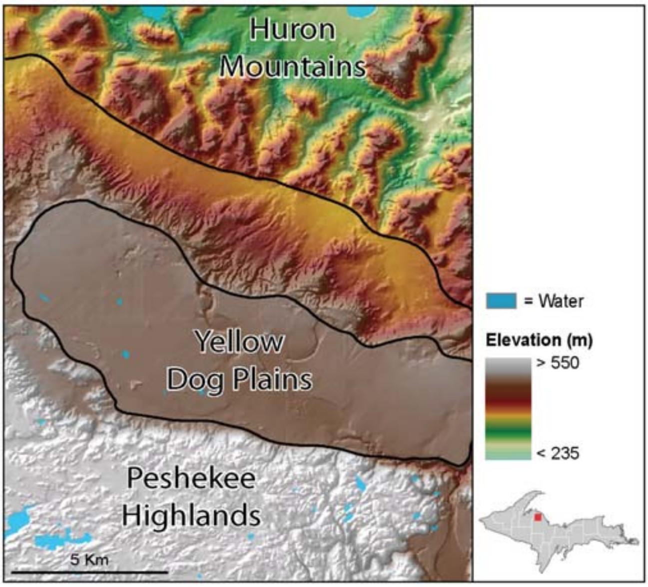

Fig. 6. Regional boundaries in the west-central Upper Peninsula, particularly illustrating where the Yellow Dog Plains meet the bedrock-controlled uplands of the Peshekee Highlands. Also shown is the high bedrock terrain of the Huron Mountains. A color elevation ramp is shown overlying the hillshade layer.

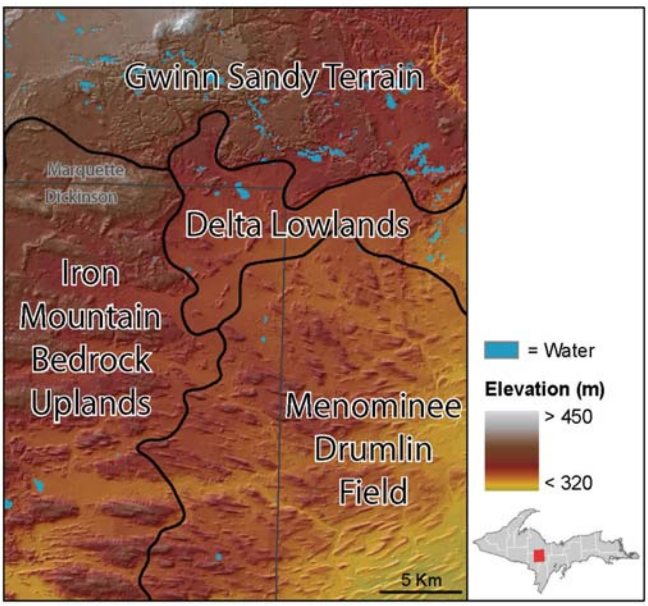

Fig. 7. Regional boundaries in the south-central Upper Peninsula, illustrating changes in landscape fabric. Note how the Menominee Drumlin field, with its many long, linear drumlins, stands in contrast to the Delta Lowlands, which lack well-formed drumlins. Similarly, the large, sculpted, sandstone bedrock outliers of the Iron Mountain Bedrock Uplands contrast with the drumlins to their east. Lastly, the physiography of the dissected, Gwinn Sandy Terrain is unlike the two regions that border it.

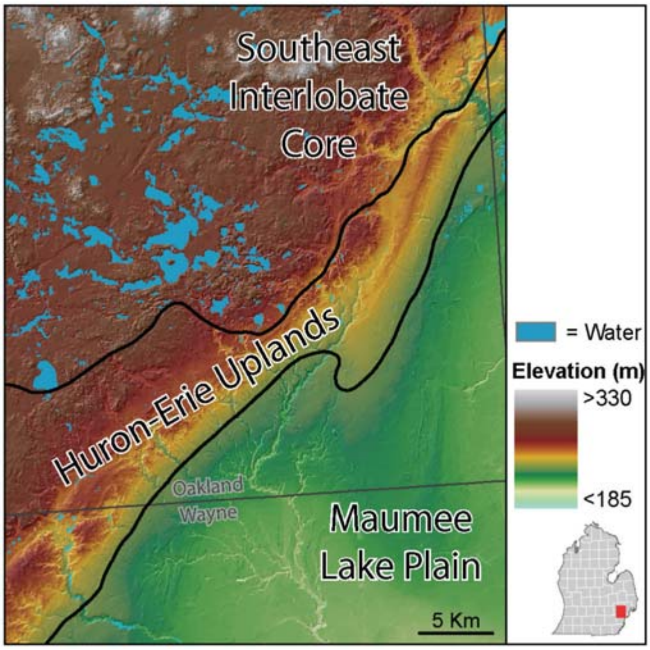

Fig. 8. Regional boundaries in southeastern Lower Michigan. The highly kettled Southeastern Interlobate Core contrasts with the long upland ridges of the Huron-Erie Drift Uplands and the low relief of the slightly river-incised, Maumee Lake Plain.

changes in glacial or postglacial processes. Regions defined by fabric, as determined by those landforms, often change abruptly to a different kind of fabric at their margins.

3. Sediment (parent material) type. We used the NRCS SSURGO soil database to define three main kinds of parent material for most of the soil map units in Michigan, loess cover notwithstanding: till, outwash, and lacustrine sediment. Parent material was an important criterion in defining many regional boundaries, as it reflects the various glacial sedimentary processes that formed these landscapes. Figure 9 illustrates the boundary between the Delta Lowlands, formed mainly on sandy loam till, and the Escanaba Sandy Plains, formed on sandy outwash. Often, as illustrated here, texture changes across boundaries coincide with parent material changes. For some other regions, the change in parent material at the boundary is not as clear and distinct as shown in Figure 9, but changes more gradually from one parent material to another.

4. Soil texture. We created shapefiles for the texture of the deepest C horizon (presumably, the soil parent material) and the uppermost mineral horizon from the NRCS SSURGO database. We developed a color scheme for each texture class, for use in our GIS project. The colors we chose were intuitive, which allowed us to visualize soil texture without having to continually recall the color legend. Sandy textures were given various yellow hues, silty textures were light blue, and clayey textures were purple-red (Fig. 10). The CMYK values of each texture class were manually adjusted so that each exhibited a hue intermediate to those adjoining it.

Although texture parameters did change abruptly at some county boundaries, due to different ages of the NRCS mapping products, both texture layers were generally very useful in delineating regional boundaries. For example, the large area of clay, clay loam and silt loam

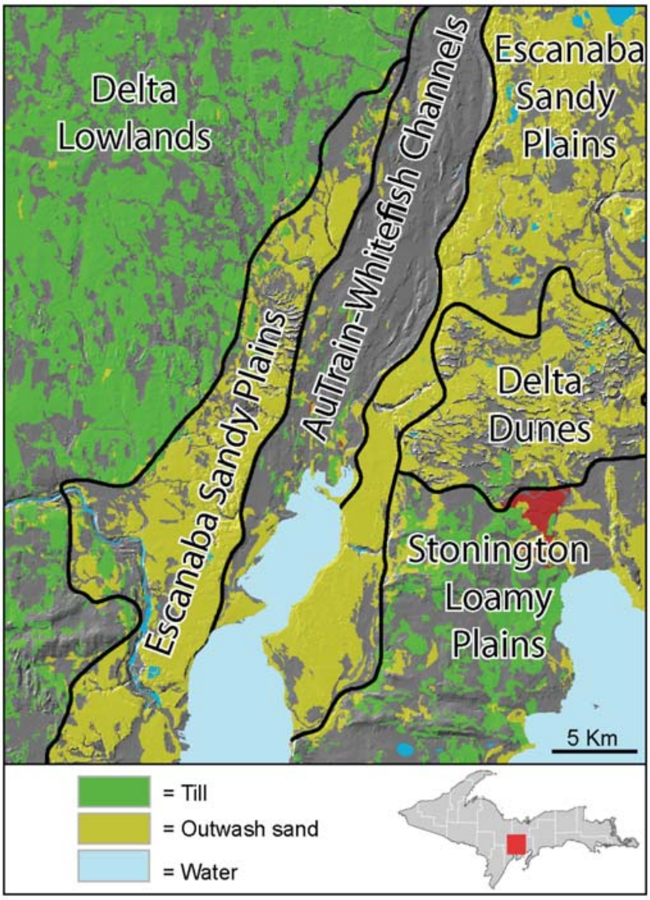

Fig. 9. Regional boundaries in the central Upper Peninsula, illustrating where the Delta Lowlands meet the Escanaba Sandy Plains. A parent material layer is shown overlying the hillshade layer. For ease of presentation, till parent materials are shown in green, lacustrine sediment in red, and outwash sediment in yellow. Soils that could not be definitively coded to a parent material are shown as the original gray color of the hillshade layer. Note also the till-dominated Stonington Loamy Plains.

parent materials of the Ontonagon Clay Plains in the western Upper Peninsula stands out in abrupt contrast to the sandy loam and sand textures of the Bessemer Plain and the Copper Range and Michigamme Bedrock Terrain, respectively (Fig. 11). The silt loam sediments of the Lake Superior Incised Plain are also obvious in Figure 10. In several of these regions, the surface material/soil textures (Fig. 12) differed from those of the parent material, although such contrasts are usually not striking.

5. Soil wetness. We employed the Natural Soil Drainage Index (DI) of Schaetzl et al. (2009) and the color ramp posted on the DI web page (http://www.drainageindex.msu.edu/) to depict the natural wetness of landscapes. This variable was particularly effective in separating swampy areas from uplands or dry sandy areas from wetter sandy areas (Fig. 13; cf. Veatch, 1939).

6. Soil patterns. There are four prominent glacial lake plains in Michigan; each constitutes a major physiographic region of the state, and all have been subdivided into two or more minor regions. Minor regions on the lake plains were delineated mainly by the pres-

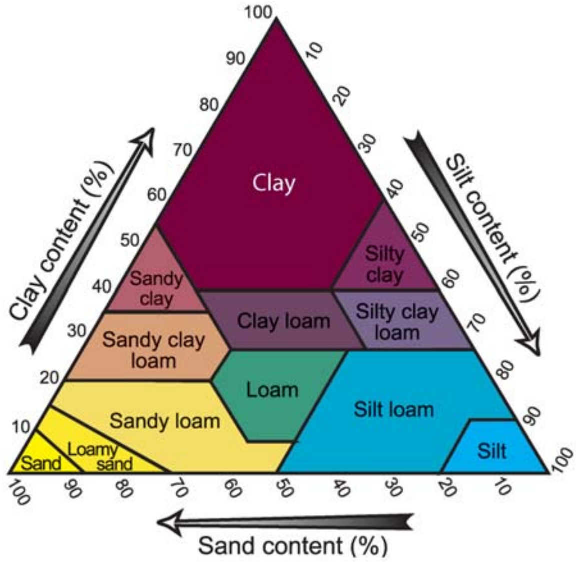

Fig. 10. The color scheme we used for depicting soil textures, shown on a standard USDA textural triangle.

ence or absence of dunes, and on surface texture (Appendix 1). However, the inland boundary of each lake plain is almost always a wave-cut bluff or shoreline that represents the highest stand of water. These wave-cut bluffs and shoreline features range from abrupt, obvious strandlines to extremely subtle changes in sediment and slope (Taylor, 1905; Leverett and Taylor, 1915; Monaghan et al., 1986, Lusch et al., 2009). We used data from Lusch et al. (2009) to determine the upper shoreline for the lakes in the Saginaw Lowlands, and data from Drzyzga et al. (2011) for Lake Algonquin. The upper shorelines of Lakes Maumee and Chicago were determined during the course of this study, using detailed DEM data and guidance from Farrand and Bell (1982a; 1982b). Data on soil patterns constituted an important advantage that was not available to prior researchers. Often, and especially for Glacial Lake Saginaw, we were able to refine this shoreline based on soil map unit shapes and patterns, as well as their drainage indexes (DIs). On the Saginaw Lake plain, soil patterns in near-shore areas, best shown by the Drainage Index layer, tended to occur in elongated map units that paralleled the paleo-shoreline. Areas out on the lake plain also had more uniform DI values, commonly in the 60–85 range. Immediately above the highest shoreline, the soil map unit patterns typically became more randomly shaped and better drained (DI values of 40–65), both of which are fairly typical of recently glaciated landscapes, especially till plains (Fig. 14).

7. *Presence of shallow bedrock*. We coded all soils in the state with a binary variable, whether they have an R horizon (bedrock) or not. This variable was particularly important in the Upper Peninsula, where several bedrock-defined regions are located (Fig. 15).

8. *Gravel in parent material*. Soil parent materials in our raster soils file were coded according to their texture descriptor for the lowermost horizon as “gravelly,” “cobbly,” or “stony.” Parent materials termed “gravelly” proved useful for discriminating areas of erosion, particularly in meltwater valleys where an erosional lag is present at depth. “Gravelly” parent materials also dominate large tracts of the interlobate regions. Areas of gravelly sediment

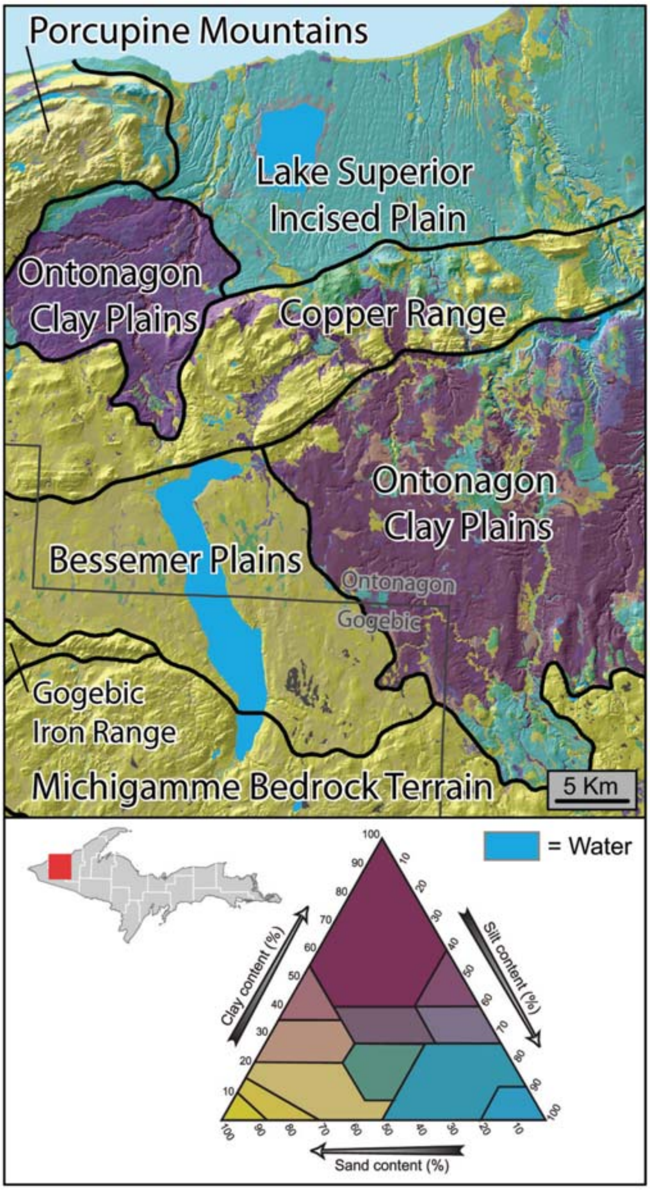

Fig. 11. Regional boundaries in the western Upper Peninsula, illustrating parent material texture contrast among the Ontonagon Clay Plains, the Bessemer Plains, the Copper Range, the Michigamme Bedrock Terrain, the Porcupine Mountains, and the Lake Superior Incised Plain. The parent material texture layer is shown overlying the hillshade layer.

stand out nicely against other areas where the sediment lacks a significant fraction of coarse fragments (Fig. 16).

9. Local relief. Relief has long been used as a criterion for delineating physical regions, e.g., Romer (1909), Partsch (1911). Our calculated index of local relief—the elevation difference for all DEM centroids within a 250-m radius—facilitated many boundary

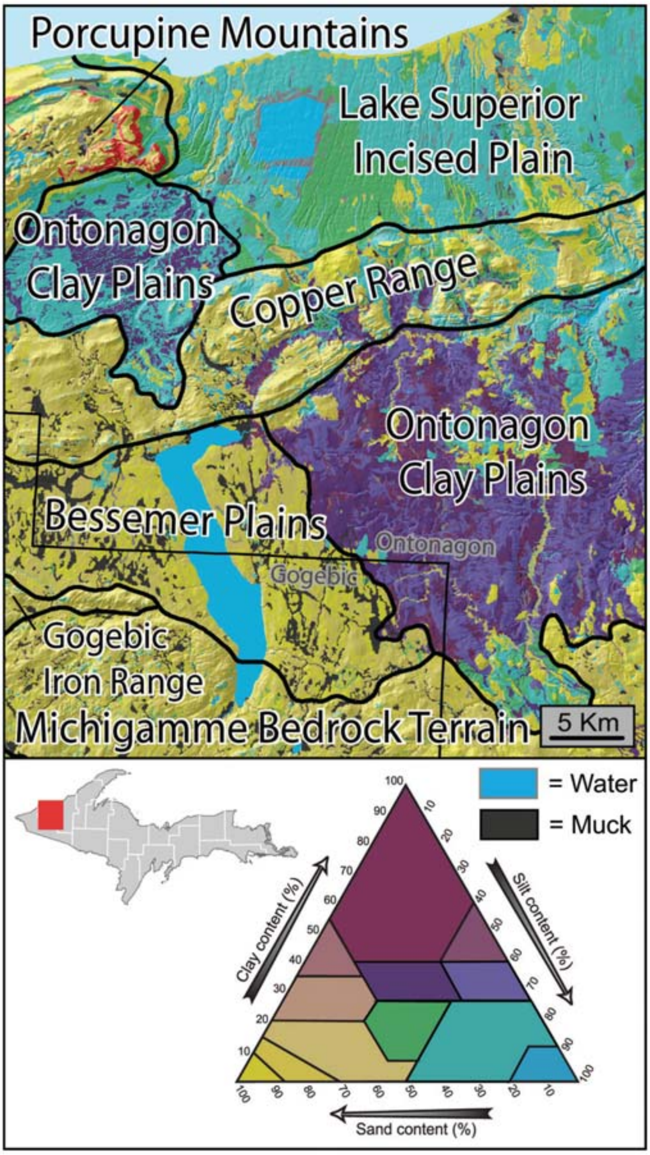

Fig. 12. This figure illustrates the same area as Fig. 11, except that surface textures are shown. The surface texture layer is shown overlying the hillshade layer. Note that muck textures (Histosols) are shown as black/dark gray.

delineations. The local relief index provided a good measure of this well-known discriminating attribute, beyond what could be gleaned from careful visual inspection of the DEM (Fig. 17). Table 3 lists the regions with the highest and lowest relief, further illustrating the utility of local relief data in physiographic delineation and description.

10. Land cover. Although land-use decisions are often a function of the biophysical characteristics of a region, land cover does not necessarily represent these characteristics directly. Nevertheless, we found land cover to be a useful criterion to define some regio-

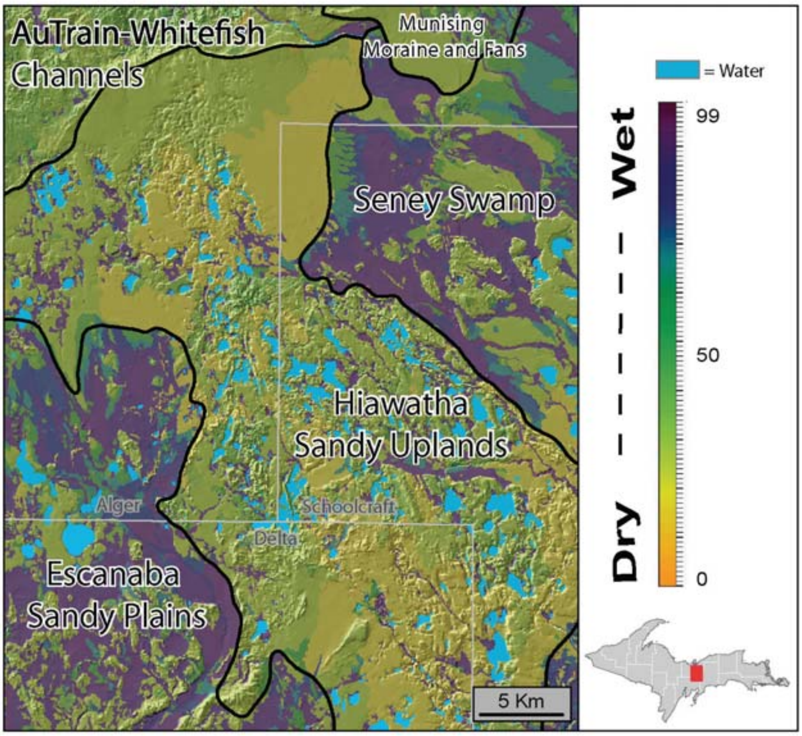

Fig. 13. Regional boundaries in the central Upper Peninsula, where most of the landscape is sandy, but natural soil wetness varies markedly from region to region. Shown here are the sandy, generally upland landscape of the Hiawatha Sandy Uplands, which contrasts with the sandy but much wetter Escanaba Sandy Plains and the Seney Swamp. This figure was created by draping the partially transparent Natural Soil Drainage Index (Schaetzl et al., 2009) color ramp over a hillshade layer.

nal boundaries. Often, land cover and cropping patterns effectively integrated the many subtleties of soils, topography and hydrology. Frequently, land-cover patterns also served as a "check" on our initial boundary delineations. Figure 18 illustrates how land cover clearly defined the boundary between two regions within a National Forest, where soils information is not as detailed (or perhaps even as accurate) as in other areas. Here, land cover helped us to refine the boundary between the Ludington Loamy Hills and the adjoining sandier regions. In a similar way, crop patterns helped us define and confirm several regional boundaries (Fig. 19).

11. Water table depth. The main advantage of this data layer was its ability to highlight subtle variations in topography. The water table occurs much deeper in upland terrain. The water table depth data enhanced topographic transitions to lower areas and emphasized slight topographic escarpments and major uplands (Fig. 20).

Other physical measures of the landscape also were consulted while drawing regional boundaries (Table 2). For example, bedrock geology separates the Iron Mountain Bedrock Uplands, which have numerous outliers of Munising sandstone that support isolated hills, from the Michigamme Bedrock Terrain, where the sandstone bedrock is absent. Neither drift thickness nor bedrock elevation was ever a sole criterion for a regional boundary, but both were consulted and often roughly coincided with boundaries. These two data layers are not as spatially precise as some others, because they are based on water, oil and gas well data,

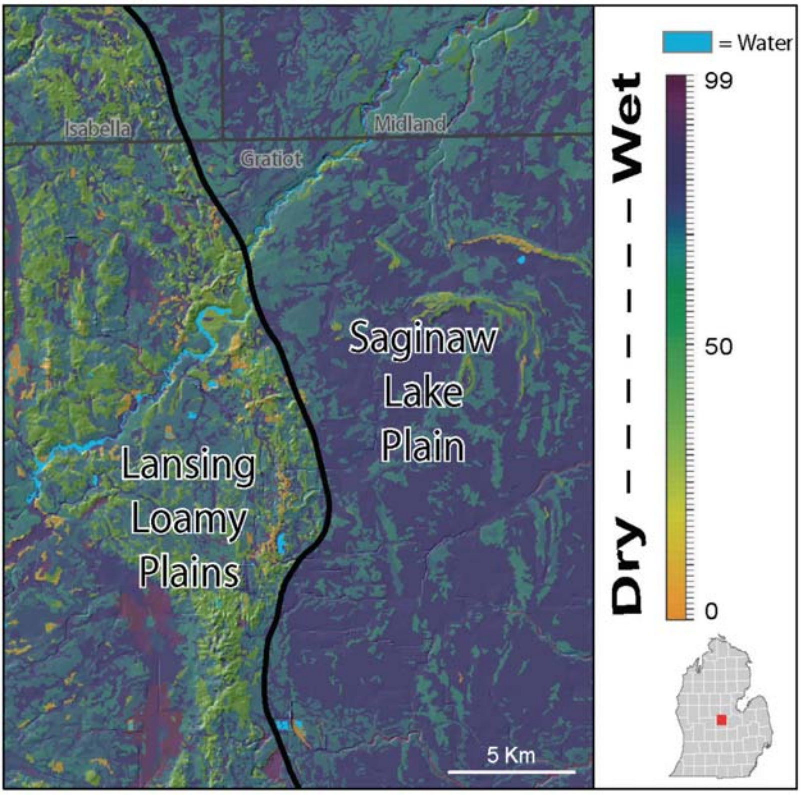

Fig. 14. Regional boundaries at the edge of the Saginaw Lake Plain, in the central Lower Peninsula, as shown with the Natural Soil Drainage Index (DI). Note how the soil patterns and DI values change markedly across the boundary from the Lansing Loamy Plains to the Saginaw Lake Plain.

which are spotty in some areas but dense in others. Accordingly, the quality of the data can vary greatly.

We acknowledge the great service done for us by scholars who have participated in previous surficial and physiographic mapping efforts (Table 2). Many of the resultant maps were extremely helpful to our mapping effort and illustrate the point that two maps, each quite different, can both be "correct," depending on the purpose of the map itself.

Validity of the GIS/Mapping Approach/Technique

To the map user, a first question might be, "Why are these region definitions or boundaries better than what has been done previously?" This is a legitimate concern; we argue below that the multi-faceted approach taken here should help mollify such apprehensions. One possible way to legitimize our boundary definitions would be via validation, i.e., testing our predictive map against preexisting ones (Table 2). We rejected this approach because it assumes that older maps somehow represent reality better than our map does. Each of the former physiographic maps of Michigan made use of more and better data in its compilation, as compared to its predecessors, as did ours. To compare our map to those that came before, i.e., those produced with lesser data, would not be useful as a validation exercise and could even be viewed as an exercise designed only to show the superiority of our product. We also

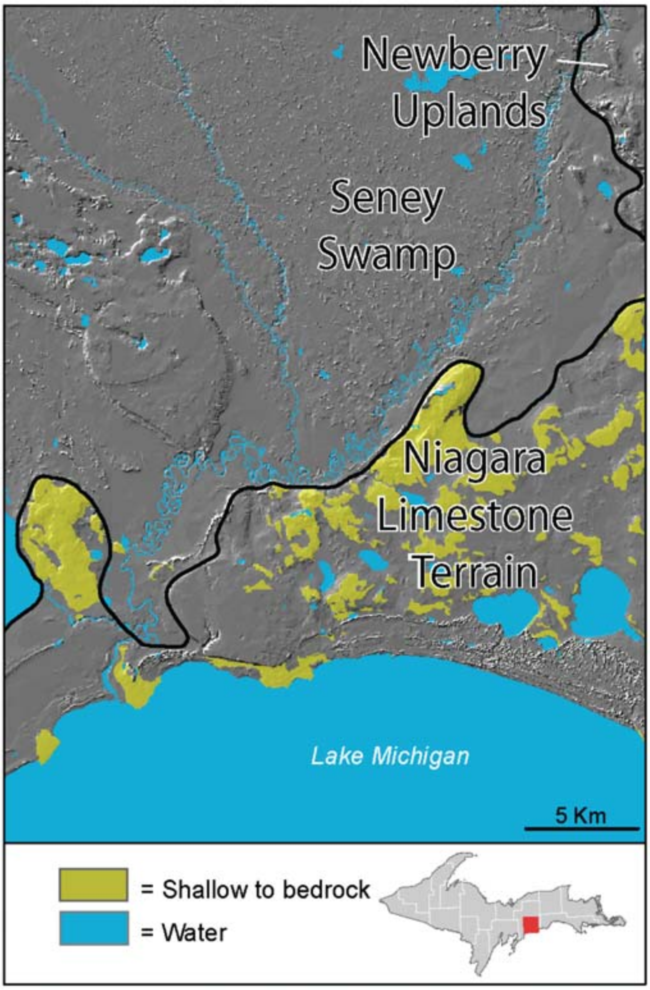

Fig. 15. Regional boundaries in the Upper Peninsula, near Lake Michigan. Soils in the Niagara Limestone Terrain are often shallow to bedrock (highlighted here in yellow), especially near its prominent bedrock escarpment.

note that an effort to compare the within-region homogeneity of our map vis-à-vis others is beyond the scope of our study. We have divided the state into far more regions, of greater internal homogeneity, than did many early authors. To compare our work to theirs would serve little useful purpose.

To circumvent this dilemma, we chose to examine the efficacy of the region boundaries in another manner. We assumed that boundaries are best drawn at locations where (in this case, physical) criteria change most abruptly or rapidly. This “boundary change” can be manifested in two different ways: (1) at the boundary one type of physical attribute (e.g., sandy soils) ends and is replaced with another (e.g., silty soils), or (2) the rate of change in a physical attribute is maximal at the boundary. Many natural/physical boundaries exhibit these characteristics for one or more physical attributes. We argue that the more attributes that change across a boundary, the more defendable and therefore, the more “real” it is. To that end, we examined the 224 unit boundaries on the Michigan physiographic map, to determine how

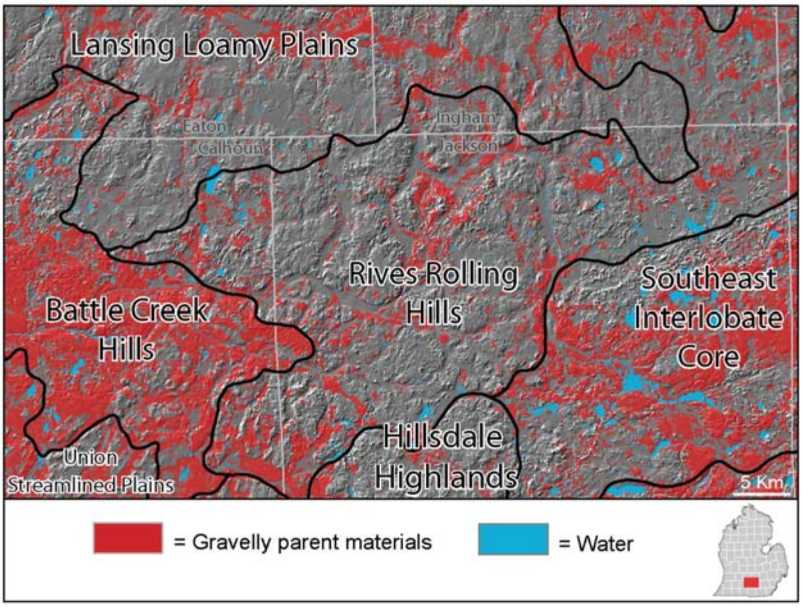

Fig. 16. Regional boundaries in the southern Lower Peninsula. Gravelly parent materials are shown in red; the spatial frequency of gravelly soils changes markedly across the boundary between the Rives Rolling Hills and the Battle Creek Hills. Note also that the distribution of gravelly soil parent materials is different between the Rives Rolling Hills, where the few gravelly parent materials that do exist are mainly in valleys or valley-side slopes, and the Southeastern Interlobate Core, where large parts of the uplands are covered with gravelly parent materials.

many physical attributes change across each of them. Theoretically, "better" boundaries, i.e., produced via better mapping protocols, should exhibit more instances of change.

Table 4 lists the various boundary criteria used in this mapping project, by frequency of occurrence. As has been found on many physiographic maps, relief was the most commonly used criterion in the determination of regional boundaries. The soil drainage index, the presence of an escarpment, and the fabric (or physical arrangement) of the landscape were ranked second, third, and fourth, respectively. This finding reinforces the importance of physical surface features (those readily viewable on the land surface), to the delineation of physiographic boundaries. A second set of important and commonly used criteria focus on soil and sediment characteristics, i.e., the Drainage Index of Schaetzl et al. (2009), as well as parent material type and soil surface textures. In a generally constructional, geologically young landscape like Michigan, where sediments vary noticeably across space as a function of glacial depositional environments, both of these findings are not surprising.

Lastly, Figure 21 shows the number of map boundaries that occur based on a change in one, two, three, or more attributes. These data show that almost 80% of the boundaries on the Michigan physiographic map are based on three or more criteria, and more than half of the boundaries are based on four or more criteria. These observations demonstrate that many of the physical attributes of the Michigan landscape change synchronously at our delineated boundaries and thereby underscore the efficacy of our boundary selections.

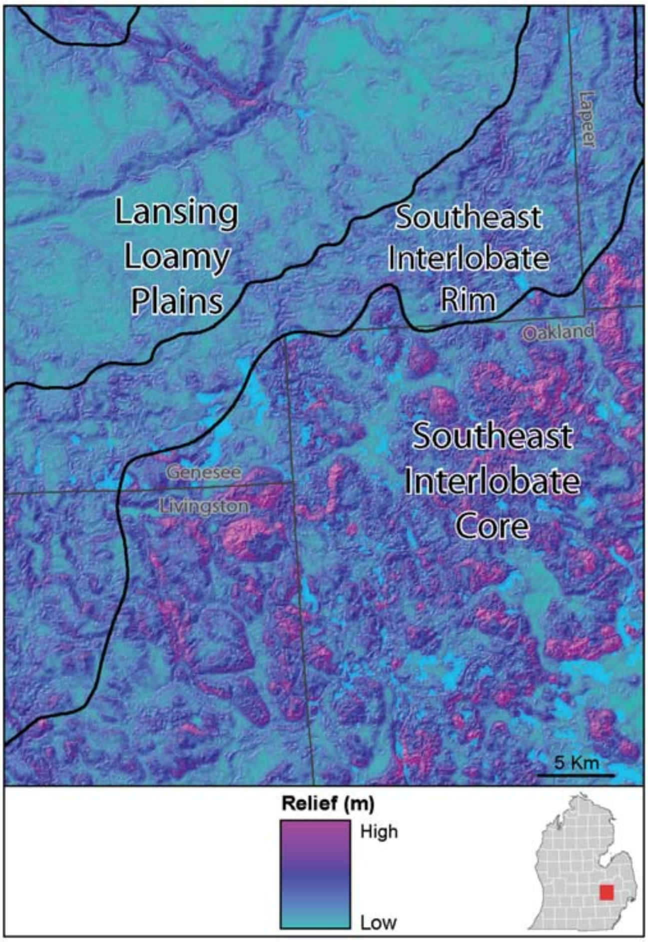

Fig. 17. Regional boundaries in southeastern Lower Michigan. Because of the complexity of the soils in the two interlobate areas, shown here, soil attributes had limited use in separating these areas from each other. However, local relief, displayed here, often worked very well as a discriminating criterion.

Importance and Innovativeness of the Michigan Physiographic Map Exercise

The new physiographic map of Michigan not only provides more detail about the physical landscapes of the state than has any of its predecessors, it also pioneers pedagogic and mapping advances along several other fronts. First, the map incorporates more datasets, as well as different types of data, than do other similar maps. In particular, the detailed NRCS soil map data, used to generate spatial data on surface and subsurface textures, parent material type, and parent material graveliness, are unique and represent a methodological contribution to physical landscape mapping. Proven highly useful in our mapping exercise, these data should be equally helpful to similar mapping and GIS efforts elsewhere. And they are not difficult to generate from the original NRCS data, which are freely available. Second, our map may also be the first interactive, web-based physiographic map of its kind. In its online form, the physiographic map of Michigan enables users to view its contents at various scales, while at the same time allowing us to map the landscape at larger scales than would normally be possible,

Table 3. Representative Topographic Metrics for Some Physiographic Regions with High and Low Local Relief

Region name	Mean local relief[a] (m)	Standard deviation of local relief[b] (m)	"90–10" elevation difference across region[c] (m)
Five regions with the lowest local relief			
Alicia Clay Plains	0.9	1.0	10
St Clair Delta	1.0	0.8	4
Loamy Saginaw Lake Plain	2.0	1.5	74
Maumee Lake Plain	2.9	2.9	118
Saginaw Lake Plain	3.1	3.0	156
Five regions with the greatest local relief			
Huron Mountains	50.5	30.0	455
Porcupine Mountains	43.0	26.4	612
Gogebic Iron Range	33.8	20.5	278
Isle Royale	31.4	19.9	352
Peshekee Highlands	29.6	16.7	779
Five regions with the lowest elevation change (90–10)			
St Clair Delta	1.0	0.8	4
Alicia Clay Plains	0.9	1.0	10
Baraga Plains	4.3	3.7	44
Yellow Dog Plains	7.2	9.0	55
Sanilac – St Clair Loamy Plains	3.4	2.7	56
Five regions with the greatest elevation change (90-10)			
Peshekee Highlands	29.6	16.7	779
Porcupine Mountains	43.0	26.4	612
Copper Range	28.4	20.4	551
Sturgeon Incised Terrain	19.9	13.9	523
Huron Mountains	50.5	30.0	455

[a]Determined by using neighborhood analysis to calculate the elevation range in a 250-m circle for each cell within a region, and then calculating the mean of all those values for that region;[b]Similar to # note a 1 above, but the value reported is the standard deviation of the local relief measures for the region.[c]Elevation difference between the cell that is at the 90th percentile in elevation, across the entire range for a region and the cell that is at the 10th percentile in elevation.

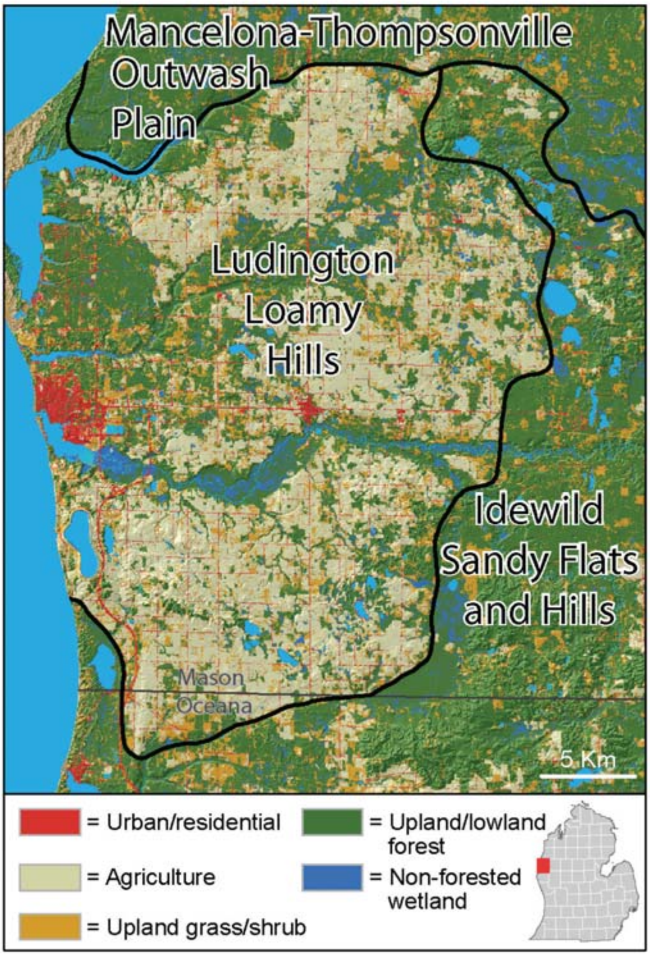

Fig. 18. Regional boundaries in western Lower Michigan. Shown here are land cover categories, draped onto a hillshade. The change in land cover between the Ludington Loamy Plains and the two, sandier, adjoining landscapes is dramatic and was partly used to define these boundaries.

had this been only a single paper map. Third, the online version of the physiographic map showcases the importance of the boundary condition by allowing a user to query the criteria used to delineate each boundary. Often—indeed, usually—maps do not provide the metadata necessary to determine the differentiating criteria of each boundary on the map. Our interactive, online map enables users to determine which landscape attributes change across each of the 336 regional boundary segments, an advantage that we view not only as unique but also highly useful from the perspective of landscape analysis.

Conclusions

We present a multi-faceted, data-rich approach to mapping the physiography of Michigan and propose that this approach marks an advance in physical geography and mapping science. Although the map thus created (Figs. 1 and 2) may be more accurate and informa-

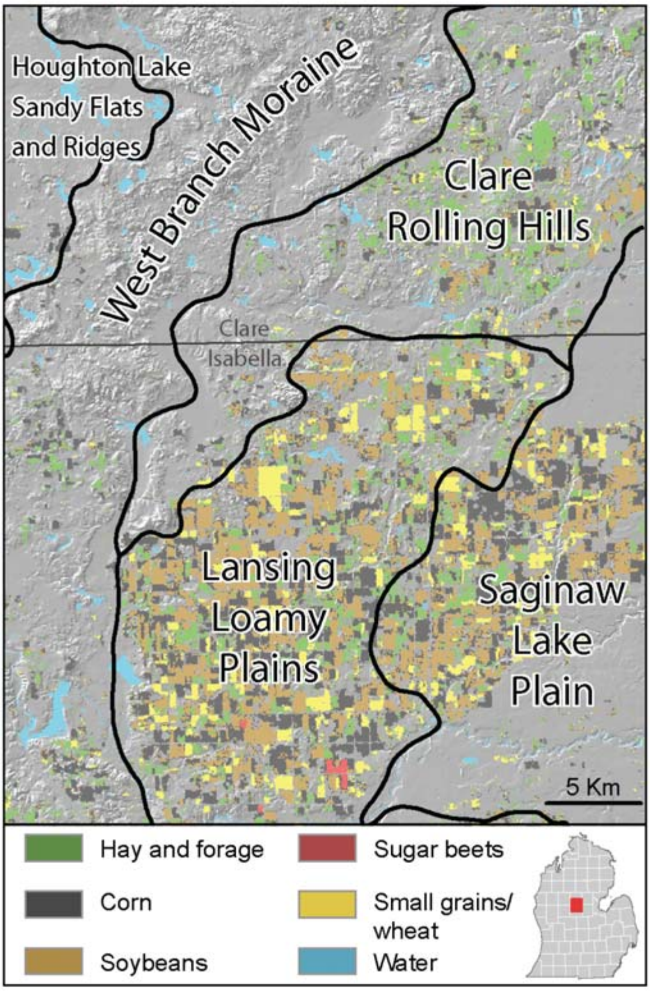

Fig. 19. Regional boundaries in central Lower Michigan. Crop patterns shown here include hay and forage, corn, soybeans, sugar beets, and small grains, usually wheat. Note that the Clare Rolling Hills are dominated by forage crops, the Lansing Loamy Plains have a rich mix of row crops and dense cropping patterns, and the West Branch moraine is largely devoid of cropland. Cropping patterns on the Saginaw Lake Plain are more variable, depending upon substrate.

tion-rich than one developed using automated, more objective, algorithm-driven approaches, we also acknowledge the extra time and wide knowledge base necessary to create such a product. Nonetheless, we believe that the boundaries we have drawn and herein defended represent, in most cases, areas of rapid and marked change on the physical landscape of Michigan, and that they are reproducible by others who might choose to use similar data and methods. This map exemplifies an innovative, object-oriented advance in physiographic mapping, using GIS and abundant digital data; it demonstrates a method that others in the geographic community can use to create reliable, detailed, and useful physiographic maps. The 91 physiographic units shown for the state are delineated at a larger scale than previously done, and each region is described thoroughly. Equally impor-

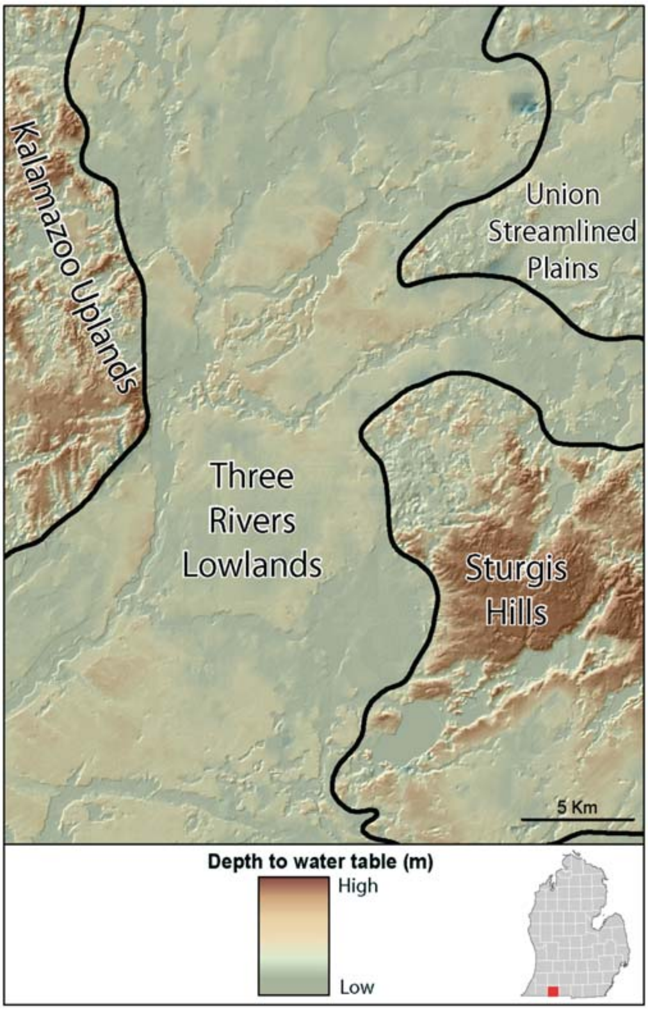

Fig. 20. Regional boundaries along the Indiana border. This figure shows the depth to water table as shades of brown, with darker shades representing deeper water tables. Note the deeper water tables on the more rugged Sturgis Hills and Kalamazoo Uplands. On the lower relief landscapes (Three Rivers Lowlands and Union Streamlined Plains), water table depths are shallower and more uniform.

tant, the criteria for the regional boundaries are clearly noted and stressed—attributes usually lacking in such maps and absent from the four, preexisting physiographic maps of Michigan.

In addition to the 10-m topographic data used in the mapping effort, soils data of various kinds provided key inputs to the final product (Johnson et al., 1995). The quality and detail of this map could not have been achieved without such information. Although this conclusion may seem to imply that maps of similar quality cannot be created without soils data, we view the proverbial glass as half full; this mapping effort showcases the tremendous biophysical mapping opportunities that exist when the NRCS SSURGO data are fully employed and "mined" to their full potential. SSURGO data generally are available for most areas within the United States and can be used to map other areas at the level of detail that we have done.

Table 4. Rank Order of Importance[a] of All Boundary Criteria for the Physiographic Map

Boundary criterion	Number of times used
Relief	132
Drainage Index	92
Escarpment	91
Landscape fabric	88
Parent material texture	79
Parent material	66
Surface soil texture	64
Elevation	41
Presettlement vegetation	39
Lake density	27
Gravel presence/absence	19
Land cover	18
Loess presence/absence	9
Dune presence/absence	8
Surficial geology	7
Drift thickness	6
Cropland	4
Geomorphology	4
Bedrock	3
Histosol density	3
Slope	2
Presence of islands	1
Stream density	1
Valley presence/absence	1

[a]Based on frequency of use

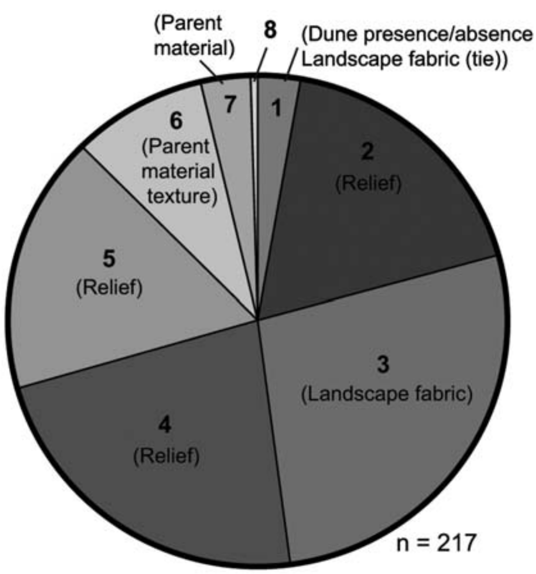

Fig. 21. Pie chart showing the proportionate number of boundaries in the physiographic map that are based on 1, 2, 3, or more (up to 8) defining criteria. The criterion (in parentheses) that was most frequently used for that group of boundaries is also shown within each slice.

Indeed, as other kinds of spatial data become more widely available, we envision that physiographic mapping efforts such as ours will become increasingly common as a way to characterize, inventory and manage Earth's physical resources.

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References

Adediran, A.O., Parcharidis, I., Poscolieri, M., & Pavlopoulos, K. (2004). Computer-assisted discrimination of morphological units on north-central Crete (Greece) by applying multivariate statistics to local relief gradients. *Geomorphology, 58*, 357–370.

Albert, D.A. (1995) Regional Landscape Ecosystems of Michigan, Minnesota, and Wisconsin: A working map and classification (4th revision). Michigan Natural Features Inventory, Lansing. Report #1995-01. 250 pp. http://www.npwrc.usgs.gov/resource/habitat/rlandscp/index.htm

Anderton, J.B., & Loope, W.L. (1995). Buried soils in a perched dunefield as indicators of Late Holocene lake-level change in the Lake Superior basin. *Quaternary Research, 44*, 190–199.

Arbogast, A.F., Hansen, E.C., & Van Oort, M.D. (2002a). Reconstructing the geomorphic evolution of large coastal dunes along the southeastern shore of Lake Michigan. *Geomorphology, 46*, 241–255.

Arbogast, A.F., & Jameson, T.P. (1998). Age estimates of inland dunes in East-Central Lower Michigan using soils data. *Physical Geography, 19*, 485–501.

Arbogast, A.F., & Loope, W.L. (1999). Maximum-limiting ages of Lake Michigan coastal dunes: Their correlation with Holocene lake level history. *Journal of Great Lakes Research, 25*, 372–382.

Arbogast, A.F., & Packman, S.C. (2004). Middle-Holocene mobilization of Aeolian sand in western Upper Michigan and the potential relationship between climate and fire. *The Holocene, 14*, 464–471.

Arbogast, A.F., Schaetzl, R.J., Hupy, J.P., & Hansen, E.C. (2004). The Holland Paleosol: An informal pedostratigraphic unit in the coastal dunes of southeastern Lake Michigan. *Canadian Journal of Earth Sciences, 41*, 1385–1400.

Arbogast, A.F., Scull, P., Schaetzl, R.J., Harrison, J., Jameson, T.P., & Crozier, S. (1997). Concurrent stabilization of some interior dune fields in Michigan. *Physical Geography, 18*, 63–79.

Arbogast, A.F., Shortridge, A.M., & Bigsby, M.E. (2009). Using volumetric estimates of eolian sand to explain the geography of coastal sand dunes in Lower Michigan. *Physical Geography, 30*, 479–500.

Arbogast, A.F., Wintle, A.G., & Packman, S.C. (2002b). Widespread middle Holocene dune formation in the eastern Upper Peninsula of Michigan and the relationship to climate and outlet-controlled lake level. *Geology, 30*, 55–58.

Arrell, K.E., Fisher, P.F., Tate, N.J., & Bastin, L. (2007). A fuzzy c-means classification of elevation derivatives to extract the morphometric classification of landforms in Snowdonia, Wales. *Computers and Geosciences, 33*, 1366–1381.

Asselen, S.V., & Seijmonsbergen, A.C. (2006). Expert-driven semi-automated geomorphological mapping for a mountainous area using a laser DTM. *Geomorphology, 78*, 309–320.

Attig, J.W., Clayton, L., & Mickelson, D.M. (1985). Correlation of late Wisconsin glacial phases in the western Great Lakes area. *Geological Society of America Bulletin, 96*, 1585–1593.

Barrett, L.R. (1997). Podzolization under forest and stump prairie vegetation in northern Michigan. *Geoderma, 78*, 37–58.

Barrett, L.R. (1998). Origin and history of stump prairies in northern Michigan: forest composition and logging practices. *Great Lakes Geographer, 5*, 105–123.

Barrett, L.R., Liebens, J., Brown, D.G., Schaetzl, R.J., Zuwerink, P., Cate, T.W., & Nolan, D.S. (1995). Relationships between soils and presettlement vegetation in Baraga County, Michigan. *American Midlands Naturalist, 134*, 264–285.

Battle, J., Anderton, J., & Schaetzl, R.J. (2009). Isle Royale. In R.J. Schaetzl, J.T. Darden, & D. Brandt (Eds.), *Michigan Geography and Geology* (pp. 377–388). Boston, MA: Pearson Custom Publishing.
Blewett, W.L. (1990) The glacial geomorphology of the Port Huron complex in northwestern southern Michigan. PhD Dissertation, Department of Geography, Michigan State University. 191 pp.
Blewett, W.L. (1991). Characteristics, correlations, and refinement of Leverett and Taylor's Port Huron Moraine in Michigan. *East Lakes Geographer, 26*, 52–60.
Blewett, W.L. (1994) Late Wisconsin history of Pictured Rocks National Lakeshore and vicinity. Pictured Rocks Resource Report 94–01. 8 pp.
Blewett, W.L. (1995). Deglaciation of the Port Huron moraine in northwestern Lower Michigan. *Great Lakes Geographer, 2*, 1–14.
Blewett, W.L., & Rieck, R.L. (1987). Reinterpretation of a portion of the Munising moraine in northern Michigan. Ge*ological Society of America Bulletin, 98*, 169–175.
Blewett, W.L., & Winters, H.A. (1995). The importance of glaciofluvial features within Michigan's Port Huron moraine. *Annals of the Association of American Geographers, 85*, 306–319.
Blewett, W.L., Winters, H.A., & Rieck, R.L. (1993). New age control on the Port Huron moraine in northern Michigan. *Physical Geography, 14*, 131–138.
Bornhorst, T.J., & Lankton, L.D. (2009). Copper Mining: A Billion Years of Geologic and Human History. In R.J. Schaetzl, J.T. Darden, & D. Brandt (Eds.), *Michigan Geography and Geology* (pp. 150–173). Boston, MA: Pearson Custom Publishing.
Bretz, J.H. (1951a). Causes of the glacial lake stages in Saginaw Basin, Michigan. *Journal of Geology, 59*, 244–258.
Bretz, J.H. (1951b). The stages of Lake Chicago: Their causes and correlations. *American Journal of Science, 249*, 401–429.
Brockman, C.S. (1998) Physiographic regions of Ohio. Ohio Dept of Natural Resources, Division of Geological Survey. http://www.epa.state.oh.us/portals/27/SIP/SO2/D2_physio.pdf
Brown, D.G., Lusch, D.P., & Duda, K.A. (1998). Supervised classification of types of glaciated landscapes using digital elevation data. *Geomorphology, 21*, 233–250.
Brown, S.E., Fisher, T.G., Kehew, A.E., and Taylor, L.D. (1999) Pleistocene geology of north-central Indiana and south-central Michigan, guidebook for the 45th Midwest Friends of the Pleistocene Field Conference. Indiana Geological Survey Open-file Study 99–1. 77 pp.
Brye, K.R. (2009). Potential observation reduction for characterizing a suite of soil surface properties in native prairies in the midsouthern United States. *Soil Science, 174*, 516–522.
Burgis, W.A. (1977) Late-Wisconsinan history of northeastern Lower Michigan. PhD Dissertation, Department of Geology, University of Michigan. 396 pp.
Burrough, P.A., van Gaans, P.F.M., & MacMillan, R.A. (2000). High-resolution landform classification using fuzzy k-means. *Fuzzy Sets and Systems, 113*, 37–52.
Butterfield, I.W. (1986). Water configurations in the environment from the Main Algonquin to the Nipissing I stages of the Great Lakes in the Saginaw Valley, Michigan. *Michigan Archaeologist, 32*, 101–137.
Camargo, F.F., Florenzano, T.G., de Almeida, C.M., & de Oliveira, C.G. (2009). Geomorphological mapping using object-based analysis and ASTER DEM in the Paraíba do Sul Valley, Brazil. *International Journal of Remote Sensing, 30*, 6613–6620.
Clark, W.Z.Jr., & Zisa, A.C. (1976). *Physiographic Map of Georgia*. Atlanta, GA: Georgia Department of Natural Resources.
Comer, P.J., Albert, D.A., Wells, H.A., Hart, B.L., Raab, J.B., Price, D.L., Kashian, D.M., Corner, R.A., and Schuen, D.W. (1995) Michigan's native landscape, as interpreted from the General Land Office surveys 1816-1856. Report to the US EPA Water Division and the Wildlife Division, Michigan Department of Natural Resources, Michigan Natural Features Inventory, Lansing. 78 pp. and digital map. http://www.mcgi.state.mi.us/mgdl/
Daly, C., Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., Curtis, J., & Pasteris, P.P. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology, 28*, 2031–2064.
Dikau, R., Brabb, E.E., Mark, R.K., and Pike, R.J. (1995) Morphometric landform analysis of New Mexico. In: Pike RJ and Dikau R (eds). Advances in Geomorphometry. *Zeitschrift fur Geomorphologie, Supplementband*, Vol. 101, 109-126.
Dodson, R.L. (1985) Topographic and sedimentary characteristics of the Union streamlined plain and surrounding morainic areas. Ph.D. Dissertation, Dept. of Geography, Michigan State University, East Lansing, MI.

Dragut, L., & Blaschke, T. (2006). Automated classification of landform elements using object-based image analysis. *Geomorphology, 81*, 330–344.

Drzyzga, S.A., Shortridge, A.M., and Schaetzl, R.J. (2011) Mapping the stages of Glacial Lake Algonquin in northern Michigan, USA, and nearby Ontario, Canada, using an isostatic rebound model. *Journal of Paleolimnology*, Vol. 46, in press.

Durand, L. (1933). *Physiographic diagram of Wisconsin*. Maplewood, NJ: The Geographical Press, Hammond Inc..

Eschman, D.F., Farrand, W.R., and Evenson, E.B. (1973) Pleistocene geology of the northwestern quarter southern peninsula, Michigan. In *Geology and the Environment. Man, Earth, and Nature in Northwestern Lower Michigan*. Michigan Basin Geological Society Miscellaneous, Publication, 14–18.

Farrand, W.R. (1960). *Evidence of ancient levels of Lake Superior in the Huron Mountains area*Report prepared for the Huron Mountain Wildlife Foundation.

Farrand, W.R. (1988) The Glacial Lakes around Michigan. Michigan Department of Environmental Quality, Bulletin 4.

Farrand, W.R. and Bell, D.L. (1982a) Quaternary Geology of Northern Michigan. 1:500,000-scale. Department of Natural Resources, Geological Survey Division, Lansing, Michigan.

Farrand, W.R. and Bell, D.L. (1982b) Quaternary Geology of Southern Michigan. 1:500,000 scale. Department of Natural Resources, Geological Survey Division, Lansing, Michigan.

Farrand, W.R. and Drexler, C.W. (1985) Late Wisconsinan and Holocene history of the Lake Superior basin. In: Quaternary Evolution of the Great Lakes. In: P.F. Karrow and P.E. Calkin, eds., *Geological Association of Canada Special Paper* 30: 17-32.

Farrand, W.R., & Eschman, D.F. (1974). Glaciation of the southern peninsula of Michigan: A review. *Michigan Academician, 7*, 31–56.

Fearer, T.M., Norman, G.W., Pack, J.C., Bittner, S., & Healy, W.M. (2008). Influence of physiographic and climatic factors on spatial patterns of acorn production in Maryland and Virginia, USA. *Journal of Biogeography, 35*, 2012–2025.

Fenneman, N.M. (1917). Physiographic divisions of the United States. *Annals of the Association of American Geographers, 6*, 19–98.

Fisher, T.G., Jol, H.M., & Boudreau, A.M. (2005). Saginaw Lobe tunnel channels (Laurentide ice sheet) and their significance in south-central Michigan. *Quaternary Science Reviews, 24*, 2375–2391.

Fisher, T.G., & Taylor, L.D. (2002). Sedimentary and stratigraphic evidence for subglacial flooding, south-central Michigan, USA. *Quaternary International, 90*, 87–115.

Gawde, A.J., Zheljazkov, V.D., Maddox, V., & Cantrell, C.L. (2009). Bioprospection of Eastern red cedar from nine physiographic regions in Mississippi. *Industrial Crops and Products, 30*, 59–64.

Good, J.E.G., Wallace, H.L., & Williams, T.G. (1993). Management units and their use for identification, mapping and management of major vegetation types in upland conifer forest. *Forestry, 66*, 261–290.

Gray, H.H. (2000) Physiographic Divisions of Indiana. Indiana Geological Survey Special Report 61, Plate 1. Digital compilation by K.H. Sowder.

Hammond, E.H. (1963) Classes of land surface form in the forty eight states, U.S.A. *Annals of the Association of American Geographers*, Map Supplement (1:5,000,000). Vol. 54.

Hansen, E., Arbogast, A.F., & Yurk, B. (2004). The history of dune growth and migration along the southeastern shore of Lake Michigan: A perspective from Green Mountain Beach. *Michigan Academician, 35*, 455–478.

Hill, E.B. and Mawby, R.G. (1954) Types of Farming in Michigan. Michigan State College, Agricultural Experiment Station Special Bulletin 206. 80 pp.

Hupy, J.P., Aldrich, S., Schaetzl, R.J., Varnakovida, P., Arima, E., Bookout, J., Wiangwang, N., Campos, A., & McKnight, K. (2005). Mapping soils, vegetation, and landforms: An integrative physical geography field experience. *Professional Geographer, 57*, 438–451.

Iwahashi, J., & Pike, R.J. (2007). Automated classifications of topography from DEMs by an unsupervised nested-means algorithm and a three-part geometric signature. *Geomorphology, 86*, 409–440.

Johansen, K., Coops, N.C., Gergel, S.E., & Stange, Y. (2007). Application of high spatial resolution satellite imagery for riparian and forest ecosystem classification. *Remote Sensing of Environment, 110*, 29–44.

Johnson, P.A., & Fecko, B.J. (2008). Regional channel geometry equations: A statistical comparison for physiographic provinces in the eastern US. *River Research and Applications, 24*, 823–834.

Johnson, R.R., Higgins, K.F., & Hubbard, D.E. (1995). Using soils to delineate South Dakota physiographic regions. *Great Plains Research, 5*, 309–322.

Johnson, W.H., Hansel, A.K., Bettis, E.A.III, Karrow, P.F., Larson, G.J., Lowell, T.V., & Schneider, A.F. (1997). Late Quaternary temporal and event classifications, Great Lakes Region, North America. *Quaternary Research, 47*, 1–12.

Kehew, A.E., Beukema, S.P., Bird, B.C., & Kozlowski, A.L. (2005). Fast flow of the Lake Michigan Lobe: evidence from sediment-landform assemblages in southwestern Michigan, USA. *Quaternary Science Reviews, 24*, 2335–2353.

Kehew, A.E., Nicks, L.P., & Straw, W.T. (1999). Palimpsest tunnel valleys: evidence for relative timing of advances in an interlobate area of the Laurentide Ice Sheet. *Annals of Glaciology, 28*, 47–52.

Kilic, S., Evrendilek, F., Senol, S., & Celik, I. (2005). Developing a suitability index for land uses and agricultural land covers: A case study in Turkey. *Environmental Monitoring and Assessment, 102*, 323–335.

Kozlowski, A.L., Kehew, A.E., & Bird, B.C. (2005). Outburst flood origin of the Central Kalamazoo River Valley, Michigan, USA. *Quaternary Science Reviews, 24*, 2354–2374.

Krist, F.J.Jr., & Lusch, D.P. (2004). Glacial history of Michigan, U.S.A.: A regional perspective. In J. Ehlers & P.L. Gibbard (Eds.), *Quaternary Glaciations - Extent and Chronology* (pp. 111–117). Amsterday: Elsevier.

Krist, F.Jr., & Schaetzl, R.J. (2001). Paleowind (11,000 BP) directions derived from lake spits in northern Michigan. *Geomorphology, 38*, 1–18.

Larsen, C.E. (1974) Late Holocene lake levels in southern Lake Michigan. In C. Collinson, ed., *Coastal Geology, Sedimentology, and Management: Chicago and the North Shore*. Urbana, IL: Illinois State Geological Survey, Guidebook Series 12: 39-49.

Larsen, C.E., (1985) Lake level, uplift, and outlet incision, the Nipissing and Algoma Great Lakes. In P. F. Karrow and P.E. Calkin, eds., *Quaternary Evolution of the Great Lakes*. Geological Association of Canada Special Paper 30, 63-77.

Larsen, C.E. (1987) Geological history of glacial Lake Algonquin and the upper Great Lakes. US Geological Survey Bulletin 1801. 36 pp.

Larson, G.J., Lowell, T.V., & Ostrom, N.E. (1994). Evidence for the Two Creeks interstade in the Lake Huron basin. *Canadian Journal of Earth Sciences, 31*, 793–797.

Larson, G., & Schaetzl, R.J. (2001). Origin and evolution of the Great Lakes. *Journal of Great Lakes Research, 27*, 518–546.

Leighton, M.M., Ekblaw, G.E., & Horberg, L. (1948). Physiographic divisions of Illinois. *Journal of Geology, 56*, 16–33.

Leverett, F., & Taylor, F.B. (1915). *The Pleistocene of Indiana and Michigan and the history of the Great Lakes* (53). , U.S: Geological Survey Monograph.

Loope, W.L., & Arbogast, A.F. (2000). Dominance of a ~150 year cycle of sand supply change in Late Holocene dune-building along the eastern shore of Lake Michigan. *Quaternary Research, 54*, 414–422.

Loope, W.L., Fisher, T.G., Jol, H.M., Goble, R.J., Anderton, J.B., & Blewett, W.L. (2004). A Holocene history of dune-mediated landscape change along the southeastern shore of Lake Superior. *Geomorphology, 61*, 303–322.

Lowell, T.V., Larson, G.J., Hughes, J.D., & Denton, G.H. (1999). Age verification of the Lake Gribben forest bed and the Younger Dryas Advance of the Laurentide Ice Sheet. *Canadian Journal of Earth Sciences, 36*, 383–393.

Lusch, D.P. (1982) The origin and morphogenetic significance of patterned ground in the Saginaw Lowland of Michigan. PhD Dissertation, Department of Geography, Michigan State University, East Lansing, MI. 152 pp.

Lusch, D.P., Reeves, H., and Miller, S. (2005) Technical Report, Groundwater Inventory and Mapping Project. Water Bureau, Michigan Department of Environmental Quality. 248 pp. (http://gwmap.rsgis.msu.edu/Technical_Report.pdf).

Lusch, D.P., Stanley, K.E., Schaetzl, R.J., Kendall, A.D., van Dam, R.L., Nielsen, A., Blumer, B.E., Hobbs, T.C., Archer, J.K., Holmstadt, J.L.F., & May, C.L. (2009). Characterization and mapping of patterned ground in the Saginaw Lowlands, Michigan: Possible evidence for Late-Wisconsin permafrost. *Annals of the Association of American Geographers, 99*, 445–466.

Martin, H.M. (1955) Map of the Surface Formations of the Southern Peninsula of Michigan. Michigan Geological Survey, Publication 49. 1:500,000 scale.

Martin, H.M. (1957) Map of the Surface Formations of the Northern Peninsula of Michigan. Michigan Geological Survey, Publication 49. 1:500,000 scale.

Martin-Duque, J.F., Pedraza, J., Sanz, M.A., Bodoque, J.M., Godfrey, A.E., Diez, A., & Carrasco, R.M. (2003). Landform classification for land use planning in developed areas: An example in Segovia Province (Central Spain). *Environmental Management, 32*, 488–498.

McGrain, P. (1983). *The geologic story of Kentucky*. Lexington, KY: Kentucky Geological Survey, University of Kentucky.

Melhorn, W.N. (1954) Valders glaciation of the Southern Peninsula of Michigan. PhD Dissertation, University of Michigan.

Michigan Department of Natural Resources. Forest, Minerals and Fire Management Division (2003) Integrated Forest Monitoring Assessment and Prescription (IFMAP) / GAP Landuse/Landcover for Michigan, version 1. Time-period of content 1997-2001 for remotely-sensed TM satellite data. http://www.mcgi.state.mi.us/mgdl/.

Miliaresis, G.C., & Argialas, D.P. (1999). Segmentation of physiographic features from the global digital elevation model/GTOPO30. *Computers and Geosciences, 25*, 715–728.

Milstein, R.L. (1987) Bedrock geology of Southern Michigan. Geological Survey Division, Michigan Department of Natural Resources. 1:500,000-scale.

Millar, S.W.S. (2004). Identification of mapped ice-margin positions in western New York from digital terrain-analysis and soil databases. *Physical Geography, 25*, 347–359.

Monaghan, G.W., Fay, L., & Lovis, W.A. (1986). Nipissing transgression in the Saginaw Bay region, Michigan. *Canadian Journal of Earth Sciences, 23*, 1851–1854.

National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (2008) C-CAP zone 41 2006-Era Land Cover. Time period of content 2005-2006. http://www.csc.noaa.gov/digitalcoast/data/ccapregional/

Natural Resources Conservation Service (2006) Landforms of the Upper and Northern Lower Peninsula of Michigan. http://www.mi.nrcs.usda.gov/soils.html

Omernik, J.M. (1987). Ecoregions of the conterminous United States. *Annals of the Association of American Geographers, 77*, 118–125.

Pachauri, A.K., Gupta, P.V., & Chander, R. (1998). Landslide zoning in a part of the Garhwal Himalayas. *Environmental Geology, 36*, 325–334.

Partsch, J. (1911) Reliefenergie Niederschlesiens. In: Schlesien eine Landeskunde far das deutsche Volk. (In German). Vol. 2, Landschaften und Siedlungen: Breslau, Verlag Ferdinand Hirt. 690 pp. map scale 1:1M.

Peterson, W.L. (1985) Preliminary surficial geologic map of the Iron River 1^{o} x 2^{o} quadrangle, Michigan and Wisconsin. US Geological Survey, Open File Rept. 82-301.

Pike, R.J., & Thelin, G.P. (1990). Mapping the nation's physiography by computer. *Cartographic Perspectives, 8*, 15–24.

Quimby, G.I. (1958). Fluted points and geochronology of the Lake Michigan basin. *American Antiquity, 23*, 247–254.

Raisz, E. (1931). The physiographic method of representing scenery on maps. *Geographical Review, 21*, 297–304.

Raisz, E. and Mills, C. (1968) Landforms of Michigan. ~1:2,700,000 scale.

Reed, R.C. and Daniels, J. (1987) Bedrock geology of northern Michigan. Michigan Department of Natural Resources, Geological Survey Division. 1:500,000 scale.

Rhoads, B.L., Rieck, R.L., & Winters, H.A. (1985). Effects of thick drift on Quaternary landscapes in central Michigan. *Michigan Academician, 17*, 301–315.

Rieck, R.L. (1979). Ice stagnation and paleodrainage in and near an interlobate area. *Papers of the Michigan Academy of Sciences, Arts, and Letters, 11*, 219–235.

Rieck, R.L., & Winters, H.A. (1993). Drift volume in the Southern Peninsula of Michigan–a prodigious Pleistocene endowment. *Physical Geography, 14*, 478–493.

Rieck, R.L., Winters, H.A., Mokma, D.L., & Mortland, M.M. (1979). Differentiation of surficial drift in southeastern Michigan from 7-A/10-A X-ray diffraction ratios of clays. *Geological Society of America Bulletin, 90*, 216–220.

Robinove, C.J. (1979). *Integrated terrain mapping with digital Landsat images in Queensland* (1102). , Australia: United States Geological Survey Professional Paper.

Robitaille, A., & Saucier, J.P. (1996). Land district, ecophysiographic units and areas: The landscape mapping of the Ministere des Ressources Naturelles du Quebec. *Environmental Monitoring and Assessment, 39*, 127–148.

Romer, E. (1909) Próba morfometrycznej analizy grzbietów Karpat Wschodnich. Kosmos: czasopismo Polskiego towarzystwa przyrodników im. Kopernika. Lwów., Vol. 35, 678-693.

Saha, K., Wells, N.A., & Munro-Stasiuk, M. (2011). An object-oriented approach to automated landform mapping: A case study of drumlins. *Computers and Geosciences, 37*, 1324–1336.

Salisbury, R.D. (1909). *Physiography*. New York, NY: Holt and Co..

Sathymoorthy, D., Palanikumar, R., & Sagar, B.S.D. (2007). Morphological segmentation of physiographic features from DEM. *International Journal of Remote Sensing, 28*, 3379–3394.

Schaetzl, R.J. (1998). Lithologic discontinuities in some soils on drumlins: Theory, detection, and application. *Soil Science, 163*, 570–590.

Schaetzl, R.J. (2001). Late Pleistocene ice flow directions and the age of glacial landscapes in northern Lower Michigan. *Physical Geography, 22*, 28–41.

Schaetzl, R.J. (2002). A Spodosol-Entisol transition in northern Michigan. *Soil Science Society of America Journal, 66*, 1272–1284.

Schaetzl, R.J. (2008). The distribution of silty soils in the Grayling Fingers region of Michigan: Evidence for loess deposition onto frozen ground. *Geomorphology, 102*, 287–296.

Schaetzl, R.J., & Forman, S.L. (2008). OSL ages on glaciofluvial sediment in northern Lower Michigan constrain expansion of the Laurentide ice sheet. *Quaternary Research, 70*, 81–90.

Schaetzl, R.J., & Hook, J. (2009). Characterizing the silty sediments of the Buckley Flats outwash plain: Evidence for loess in NW Lower Michigan. *Physical Geography, 29*, 1–18.

Schaetzl, R.J., & Loope, W.L. (2008). Evidence for an eolain origin for the silt-enriched soil mantles on the glaciated uplands of eastern Upper Michigan, USA. *Geomorphology, 100*, 285–295.

Schaetzl, R.J., & Weisenborn, B.N. (2004). The Grayling Fingers geomorphic region of Michigan: Soils, sedimentology, stratigraphy and geomorphic development. *Geomorphology, 61*, 251–274.

Schaetzl, R.J., Krist, F., Rindfleisch, P., Liebens, J., & Williams, T. (2000). Postglacial landscape evolution of northeastern Lower Michigan, interpreted from soils and sediments. *Annals of the Association of American Geographers, 90*, 443–466.

Schaetzl, R.J., Drzyzga, S.A., Weisenborn, B.N., Kincare, K.A., Lepczyk, X.C., Shein, K.A., Dowd, C. M., & Linker, J. (2002). Measurement, correlation, and mapping of Glacial Lake Algonquin shorelines in northern Michigan. *Annals of the Association of American Geographers, 92*, 399–415.

Schaetzl, R.J., Mikesell, L.R., & Velbel, M.A. (2006). Soil characteristics related to weathering and pedogenesis across a geomorphic surface of uniform age in Michigan. *Physical Geography, 27*, 170–188.

Schaetzl, R.J., Darden, J.T., & Brandt, D. (Eds.). (2009a). *Michigan Geography and Geology*. Boston, MA: Pearson Custom Publishers.

Schaetzl, R.J., Krist, F.J.Jr., Stanley, K.E., & Hupy, C.M. (2009). The Natural Soil Drainage Index: An ordinal estimate of long-term, soil wetness. *Physical Geography, 30*, 383–409.

Simpson, T.B., Stuart, P.E., and Barnes, B.V. (1990) Landscape ecosystems and cover types of the reserve area and adjacent lands of the Huron Mountain Club. *Occasional Papers Huron Mountain Wildlife Foundation* 4. 128 pp.

Sjogren, D.B., Fisher, T.G., Taylor, L.D., Jol, H.M., & Munro-Stasiuk, M.J. (2002). Incipient tunnel channels. *Quaternary International, 90*, 41–56.

Sommers, L.M. (Ed.). (1977). *Atlas of Michigan*. East Lansing, MI: Michigan State University Press.

Spurr, S.H., & Zumberge, J.H. (1956). Late Pleistocene features of Cheboygan and Emmet Counties, Michigan. *American Journal of Science, 254*, 96–109.

Steenfelt, A. (1993). Comparisons of geochemical patterns obtained from stream sediment, stream organics and till in the Nordkalott Project in Fennoscandia. *Journal of Geochemical Exploration, 49*, 145–159.

Stepinski, T.F., & Bagaria, C. (2009). Segmentation-based unsupervised terrain classification for generation of physiographic maps. *IEEE Geoscience and Remote Sensing Letters, 6*, 733–737.

Stoelting, P.K. (1989). Delimiting and subdividing terrain in the interlobate kettle moraine of eastern Wisconsin. *Wisconsin Geographer, 5*, 41–59.

Taylor, F.B. (1895). The Munuscong Islands. *American Geologist, 15*, 24–33.

Taylor, F. (1905) Relation of Lake Whittlesey to the Arkona beaches. 7th Annual Report of the Michigan Academy of Science, pp. 29–36.

Toppan, F.W. (1935). The Physiography of Maine. *Journal of Geology, 43*, 76–87.

United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS) (2007) Michigan Cropland Data Layer. http://datagateway.nrcs.usda.gov/

United States Department of Agriculture, Natural Resources Conservation Service (2006) Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. US Department of Agriculture, Handbook 296.

United States Geological Survey (2009) Digital Elevation Model (DEM) for Michigan from the National Elevation Dataset (NED). 10 m raster dataset. 1:24,000 scale. http://ned.usgs.gov/

United States Geological Survey (2007) National Hydrography Dataset (NHD) Stream Reach File for Michigan. 1:100,000 scale. http://nhd.usgs.gov/

Van Oort, M., Arbogast, A.F., Hansen, E.C., & Hansen, B. (2001). Geomorphological history of massive parabolic dunes, Van Buren State Park, Van Buren County, Michigan. *Michigan Academician, 33*, 175–188.

Veatch, J.O. (1930). Natural geographic divisions of land. *Papers of the Michigan Academy of Sciences, Arts and Letters, 14*, 417–432.

Veatch, J.O. (1939). Patterns based upon the distribution of swamp land in Michigan. *Papers of the Michigan Academy of Sciences, Arts and Letters, 24*, 93–106.

Veatch, J.O. (1953). *Soils and Land of Michigan*. East Lansing: Michigan State College Press.

Wahrhaftig, C. (1965) Physiographic Divisions of Alaska. US Geological Survey Professional Paper 482.

Wang, S., Laffan, W., Liu, Y., & Wu, L. (2010). Morphometric characterization of landform from DEMs. *International Journal of Geographical Information Science, 24*, 305–326.

Whitmeyer, S.J., Nicoletti, J., & De Paor, D.G. (2010). The digital revolution in geologic mapping. *Geological Society of America Today, 20*, 4–10.

Winters, H.A. and Rieck, R.L. (1980) Significance of landforms in southeast Michigan. *Annals of the Association of American Geographers*, Vol. 70, 4l3-424.

Winters, H.A., & Rieck, R.L. (1991). Late glacial terrain transformation in Michigan. *Michigan Academician, 23*, 137–148.

Yodis, E.G., & Colten, C.E. (2003). *Geography of Louisiana*. Hightstown, NJ: McGraw-Hill, Primis Custom Publishers.

Zelčs, V., & Dreimanis, A. (1997). Morphology, internal structure and genesis of the Burtnieks drumlin field, Northern Vidzeme, Latvia. *Sedimentary Geology, 111*, 73–90.

Zhalnin, A.V., & Parker, G.R. (2009). Spatial analysis and delineation of ecological landtype phases for the Hoosier National Forest, Indiana, USA. *Computers and Geosciences, 35*, 214–224.

Zumberge, J.H., & Potzer, J.E. (1956). Late Wisconsin Chronology of the Lake Michigan Basin Correlated with Pollen Studies. *Geological Society of America Bulletin, 67*, 271–288.

Appendix 1. Descriptive Information for the Physiographic Regions Defined in this Paper.[a]

Region	Physiography/relief	Soils/sediments	Hydrology	Presettlement vegetation	Land cover	Other (references)[a]
Superior Bedrock Uplands – Largely bedrock-controlled, low mountains and high hills, modified by glacial scour and deposition						
Isle Royale	Glacially scoured, bedrock island. Linear bedrock ridges and swales parallel linear trend of the island.	Swamps in swales contain Histosols. Thin, loamy, well drained soils on bedrock ridges.	Swamps, bogs and lakes, alternating with bedrock ridges.	Spruce, cedar and fir on uplands. Conifer swamp in lowlands.	National Park and UN Biosphere Reserve. Mostly forested.	Regolith thicker on SW corner of island. (Battle, Anderton, & Schaetzl, 2009)
Porcupine Mountains	High relief bedrock uplands with generally linear ridges, bedrock knobs, and broad, till-floored valleys.	Thin glacial sediment. Soils are moderately well to well drained; stony and gravelly fine sandy and loamy surface textures. Sandy loam parent materials.	Rolling landscape with several picturesque lakes set in broad valleys. Many waterfalls; heavy snow in winter.	Sugar maple-hemlock forest. More pines on bedrock ridges.	Forest; most is within a State Park.	Associated with Porcupine Mountains Wilderness State Park.
Lake Superior Incised Plain	Low-moderate relief plain, some of Glacial Lake Duluth, and generally sloping toward Lake Superior. Small, deep, parallel stream valleys drain to Lake Superior.	Upland soils are moderately well to somewhat poorly drained silt loams, loams and fine sandy loams. Parent materials are silty-sandy.	Heavy snow in winter. No lakes.	Sugar maple-hemlock-yellow birch forest.	Forest; small patches of open land.	Region has two units, separated by the Porcupine Mountains. (Larson & Schaetzl, 2001)
Ontonagon Clay Plains	Generally low to moderate relief plains, except for narrow, deep, V-shaped valleys of the deeply incised Ontonagon River.	Moderately well and well drained soils on slopes, slightly wetter on level terrain. Silt loam, clay loam and silty clay surface textures.	Ontonagon River tributaries dominate. High runoff potential due to fine-textured soils; heavy snow in winter. Few lakes.	Spruce, cedar and fir forest; sugar maple-hemlock forest on drier, more incised, and sloping areas.	Most areas remain in forest; some agriculture on some level areas.	Fine-textured tills and lacustrine sediments dominate the landscape. Region has two units, separated by the Copper Range. (Peterson, 1985)
Baraga Plains	Low relief, sandy, dry, outwash or glaciolacustrine plain.	Excessively drained, sandy soils dominate; on SE margin, very poorly drained sands occur.	Very little surface water, heavy snow in winter.	Jack and red pine forest and barrens. Conifer swamp on SE margin.	Pine forest, with areas of open land.	Driest on the north (higher) margin, increasingly wetter to the SE. Well sorted, sand parent materials. (Arbogast & Packman, 2004; Barrett et al., 1995)

[a]A brief portion of the full Appendix is reproduced here to provide a general sense of the type of information it conveys. Readers can access the full appendix as a supplement to this article in the electronic edition of Vol. 34, No. 1, of *Physical Geography*.