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A century of change in the methods, data, and approaches to mapping glacial deposits in Michigan

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ABSTRACT

Mapping of glacial deposits in Michigan dates to the very beginnings of the glacial theory in North America and logically divides into three parts: (1) early work (1885–1924) by Frank Leverett, Frank Taylor, and their colleagues, culminating in U.S. Geological Survey Monograph 53 and the publication of the first surficial geology maps for the state; (2) incremental upgrades (1925–1982) of Leverett and Taylor's work in subsequent, statewide maps by Helen Martin and William Farrand; and (3) the period since 1982, characterized by a relatively small number of detailed, process-oriented studies at various scales, including the STATEMAP and EDMAP projects and investigations led by university researchers. Progress in mapping the surficial geology of Michigan has been challenged by the complexity of glacial deposits and limited state and federal funding. The most recent maps are Farrand's statewide maps of glacial geology, which are based on the maps of Martin, which, in turn, were based on the original reconnaissance maps by Leverett and Taylor, now more than a century old. Thus, statewide maps of surficial sediments and landforms in Michigan are outmoded, often inaccurate, and in need of revision. Fortunately, new technologies and data sets are revolutionizing traditional mapping methods, creating opportunities for making cost-effective and accurate maps of Michigan's glacial deposits. Digital soils data, in particular, when viewed within a geographic information system environment, offer an especially promising avenue for improved glacial mapping.

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INTRODUCTION

The year 2015 marks the centennial of U.S. Geological Survey (USGS) Monograph 53, *The Pleistocene of Indiana and Michigan and the History of the Great Lakes*, by Leverett and Taylor (1915). This classic volume and its accompanying map (dated 1914) represent the culmination of Leverett and Taylor's glacial mapping and interpretation in the Lower (Southern) Peninsula of Michigan and form the basis for all subsequent glacial mapping in the southern part of the state.

Fourteen years later, this effort was supplemented by Leverett's *Map of the Surficial Deposits of the Lake Superior Region* (1929), which covered Michigan's Upper (Northern) Peninsula at the same scale, based on earlier reconnaissance work (Russell, 1905, 1907a, 1907b; Lane, 1908; Leverett, 1912). Over the next half-century, two additional statewide maps were produced, Martin's *Map of the Surface Formations of the Southern Peninsula of Michigan* (1955) and *Map of the Surface Formations of the Northern Peninsula of Michigan* (1957), followed much later by Farrand's *Quaternary Geology of Southern Michigan* (1982a) and *Quaternary Geology of Northern Michigan* (1982b).

The detail expressed in the maps by Leverett and Taylor in 1914 and Leverett in 1929 is impressive, but it belies the reconnaissance nature of the supporting fieldwork, which was based almost exclusively on surface morphology and boundaries of the mapping units (Russell, 1907a; Leverett, 1912; Rieck and Winters, 1981), supplemented by exposures of surficial sediments. Both Martin and Farrand unwittingly perpetuated these assumptions in their subsequent maps, because little independent fieldwork had been done in the interim. Thus, their maps were erroneously perceived by many as significant revisions and upgrades of Leverett and Taylor's original work, primarily because of their large scale, intricate nature, and sizable press runs. As we will show, few, if any, of the principal landform configurations and interpretations originally mapped by Leverett and Taylor were altered in these versions (Kehew, 2015), and their maps, at least in places, appear to be simple extensions of Leverett and Taylor's map units to accommodate details provided by topographic maps.

Recent advances in geotechnology and a better understanding of process-sediment linkages have rendered many of the classical interpretations of glacial sediments and landscapes in these maps obsolete. Unfortunately, many of these errors are perpetuated on later maps and in scientific publications. Currently, new, higher-quality topographic, hydrologic, and soils data are becoming more available and are rapidly improving in quality. In addition, the USGS is trying to improve geological interpretations throughout the region by incorporating more subsurface data in the mapping effort. Thus, the 100th anniversary of Leverett and Taylor's classic monograph is a particularly opportune time to evaluate the methods, data, and approaches to glacial mapping in Michigan over the past century.

COMPLEXITY OF MICHIGAN'S GLACIAL LANDSCAPE

Michigan's location at the confluence of six late glacial ice lobes (Huron-Erie, Saginaw, Lake Michigan, Green Bay, Chippewa, and Superior) has produced a landscape of astonishing geomorphic and sedimentological complexity. Frank Leverett, an experienced and capable geologist who mapped much of the surficial geology of the northeastern United States, was especially impressed by the variable nature of Michigan's glacial deposits, noting that "the Wisconsin drift in Michigan has perhaps greater complexity than is to be found anywhere else in the United States" (Leverett, 1904, p. 102). Geoscientists have only recently begun to understand the processes associated with these landforms and sediments (Mickelson et al., 1983; Mooers, 1990; Carlson et al., 2005; Kehew et al., 2012a, 2012b, this volume; Bird et al., this volume).

At least some of this complexity can be attributed to Michigan's location amid the deep basins of the Great Lakes. Where the advancing ice was forced up and out of the basins, shearing and compression within the glacier were maximized, leading to the incorporation of voluminous amounts of superglacial and englacial drift and to the formation of extensive, high-relief stagnation landforms, especially in the interlobate regions and northern parts of the state (Blewett et al., 2009). Additional complicating factors that have made glacial interpretation and mapping in Michigan challenging include the following:

(1) The sheer size of the state has limited any systematic mapping program beyond general reconnaissance. The state covers ~250,493 km^2 (96,716 mi^2), including 103,372 km^2 (39,912 mi^2) of inland water, making it 11th in size among the 50 states (Wright, 2006). Road mileage from Monroe in the southeastern part of the Lower Peninsula of Michigan to Ironwood at the western end of the Upper Peninsula of Michigan exceeds 1021 km (635 mi).

(2) Michigan lacks the "layer cake" stratigraphy that characterizes other states and Canadian provinces, making it difficult to establish a statewide stratigraphic framework. As a result, Michigan has few formally recognized chronostratigraphic marker beds, e.g., Kewaunee Formation, Two Creeks buried forest, etc., which are critical in determining stratigraphic context. Although distinctive strata do exist, e.g., the Holland paleosol (Arbogast et al., 2004), they often lack lateral continuity and are not spatially extensive. Together, in most cases, these shortcomings make it difficult to place individual outcrops into context and to determine meaningful long-distance correlations.

(3) Most glacial landscapes in Michigan are much more heterogeneous than originally interpreted. Many areas previously viewed as simple till plains are complex both stratigraphically and geomorphically. This is especially true across landscapes of the Saginaw Lobe, where stagnation was locally important (Kehew et al., 2012a). Likewise, many landforms mapped as "moraines" by Leverett and Taylor and similarly portrayed on subsequent maps, especially those in interlobate tracts and in the

northern part of the state, are not end moraines in the classical sense (formed predominantly of till deposited by direct glacial action), but they are better interpreted as complex ice-wastage features marking important heads of outwash. Indeed, stagnation landscapes are probably much more common in Michigan than was previously recognized.

(4) Much of the glacial sediment is coarse textured, making it difficult to differentiate sandy till from glaciofluvial sediment, especially in cored borings (Schaetzl and Weisenborn, 2004; Kehew et al., 2005). Glaciofluvial sediments appear to dominate many landscapes, especially in northern parts of the state, as well as interlobate tracts, but even here, sandy tills and sandy lake sediments may occur.

(5) The highly permeable nature of the sandy drift limits the preservation of organic materials necessary for establishing a regional radiocarbon chronology. Where organics do exist, they are often deeply buried and only accessible by drilling (Winters et al., 1986).

(6) Areas in the northern part of the Lower Peninsula of Michigan are underlain by >300 m of glacial sediments from the last glaciation (Wisconsin Episode; Rieck and Winters, 1993). Understanding the origins and significance of these sediments, especially the deeply buried ones, in the context of glacial history and mapping is difficult without exposures or detailed drilling data.

(7) The history of the numerous proglacial and postglacial lakes that formerly occupied the region (Larson and Schaetzl, 2001) is complex, with the extent and timing of many of the larger and most important lakes still unresolved. Early attempts to explain the manifestations of isostatic rebound using the "hinge line" concept have been largely discredited (Clark et al., 1990, 1994; Lewis et al., 2005), necessitating reappraisals of many of the classical interpretations of the principal glacial and early postglacial lakes and their shorelines.

(8) Modern mapping efforts have been limited in both number and extent. In Michigan and other states, research related to EDMAP, STATEMAP, and the Great Lakes Geologic Mapping Coalition projects forms the bulk of the mapping effort. These projects are typically mapped at topographic quadrangle scales of 1:24,000. At the current rate of mapping, it will take decades to complete the entire state. Aggregating these maps to a 1:500,000 scale statewide map with meaningful units and regional characterizations of their physical properties will require careful calibration.

(9) Government agencies within the State of Michigan have lagged behind other states and Canadian provinces in understanding the importance of mapping surficial geology, and they have provided little funding to support it. The Michigan Geological Survey, for example, was recently downgraded to "office" status and lacks a full-time glacial geologist. In short, since the early 1900s, glacial geology and surficial mapping have not been a priority in Michigan as it has in other Midwestern U.S. states.

All of these factors have collectively prevented cost-effective and error-free glacial mapping in Michigan. Accordingly, mapping in the state continues to be dominated by correlations based upon morphostratigraphic units and the limited surficial sediment data available, mainly from soils (Schaetzl et al., 2000, 2013; Schaetzl and Luehmann, 2013; Luehmann and Schaetzl, this volume). Herein, we review the history of glacial mapping in the state and evaluate it within the context of our current understanding of glacial processes, sediments, and landforms.

MAPPING MICHIGAN'S SURFICIAL GEOLOGY

Glacial mapping in Michigan logically divides into three parts:

(1) early work by Leverett, Taylor, and their colleagues, culminating in USGS Monograph 53 (1915) and surficial geology maps of the Lower (Southern) and Upper (Northern) Peninsulas of Michigan (Leverett, 1912, 1929; Leverett and Taylor, 1914);

(2) minor revisions of Leverett and Taylor's work by Martin (1955, 1957) and Farrand (1982a, 1982b); and

(3) the period since 1982, characterized by a relatively small number of detailed, process-oriented mapping efforts at various scales, including STATEMAP, EDMAP, and related projects, along with work by university researchers and their students.

Mapping by Leverett, Taylor, and Their Contemporaries

Background

Frank Leverett was hired in 1885 by T.C. Chamberlin, who was then the director of the USGS Division of Glacial Geology. Leverett spent the next 44 years (1885–1929) mapping glacial landforms and sediments in the Upper Midwest. Chamberlin, one of the early scientific champions of the glacial theory in America, published the first map showing all of the known moraines in the eastern United States, depicting four (Chamberlin, 1878), and later seven (Chamberlin, 1883) moraines in the Lower (Southern) Peninsula of Michigan (Fig. 1).

Frank B. Taylor studied geology and astronomy at Harvard University from 1882 to 1886 but left due to poor health. As a result, Taylor traveled (at his own expense) with a physician throughout the Great Lakes region, investigating high shorelines and former lake outlets (Leverett, 1938). Taylor's family had a home on Mackinac Island, and his first published paper in the geologic literature (Taylor, 1892) described the highest shoreline on the island. Between 1894 and 1897, Taylor published 12 papers focused on his reconnaissance work in the Superior and northern Lake Michigan and Huron Basins (Taylor, 1894a, 1894b, 1894c, 1894d, 1895a, 1895b, 1895c, 1895d, 1896a, 1896b, 1897a, 1897b). In his article on recessional moraines, he included a small-scale map of these features (Fig. 2). Taylor (1897b, p. 425) claimed, "So far as known to the writer there is no other glaciated area of like extent where a moraine series is found so simple and complete as that between Cincinnati and Mackinac."

Alfred C. Lane joined the Michigan State Geologic Survey in 1889 and later served as the state geologist from 1899 to 1909. During his tenure, much of the preliminary mapping leading to USGS Monograph 53 was completed. In cooperation with the

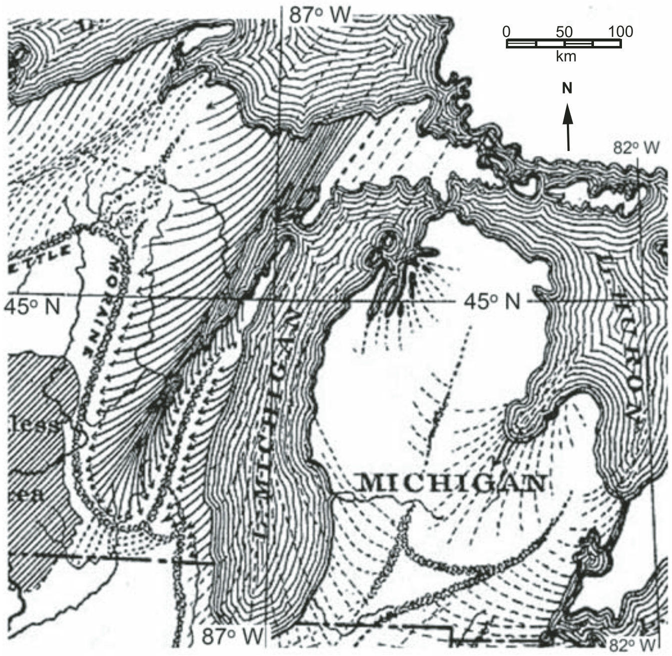

Figure 1. Earliest known map of moraines in Michigan, modified from Chamberlin (1878).

USGS, he published *Water Resources of the Lower Peninsula of Michigan* (Lane, 1899), which contained a color map (dated 1898) of the "Pleistocene Deposits of the Lower Peninsula of Michigan." This map was a compilation of published and unpublished observations by C.H. Gordon, F. Leverett, F.B. Taylor, W.H. Sherzer, and A.C. Lane (Fig. 3). Although crude by later standards, it shows the progress that these pioneers of glacial mapping had made by the end of the nineteenth century.

Later, the USGS published Leverett's (1902a) monograph on the *Glacial Formations and Drainage Features of the Erie and Ohio Basins*. This monumental work contained chapters on Glacial Lakes Maumee, Whittlesey, and Warren, especially as they related to the Imlay City and Ubly channels in Michigan. That same year, under the auspices of the Michigan Geological Survey, Taylor (1902) mapped the surficial geology of Lapeer County, and Leverett (1902b) mapped the physiography of Alcona County, delineating several moraines.

In 1903, Leverett mapped the surficial geology of the Ann Arbor 30 min quadrangle in collaboration with Professor I.C. Russell of the University of Michigan. This work was published 5 years later as Folio 155 of the *Geological Atlas of the United States* (Leverett and Russell, 1908). The "Areal Geology" map in this folio was the first and only medium-scale glacial map compiled and published by Leverett on a topographic base.

At about the same time, Russell (1905, 1907a, 1907b) published the first map showing surficial deposits of the Upper (Northern) Peninsula of Michigan restricted to a thin strip along the northern shores of Lakes Huron and Michigan. Subsequent work by Leverett in the 1905–1911 field seasons led to the publication of the first surficial geology map for the entire Upper (Northern) Peninsula of Michigan (Leverett, 1911; Fig. 4 herein). This map, augmented by extensive fieldwork in 1912–1914, 1916, and 1919, would form the basis for the much-revised *Map of the Surficial Deposits of the Lake Superior Region* (Leverett, 1929; Fig. 5 herein) that became the source for all subsequent glacial mapping in the Upper (Northern) Peninsula of Michigan.

Lane's (1908) "Summary of the Surface Geology of Michigan" contained a large-format (1:375,000) color map of the surface geology of the Lower (Southern) Peninsula of Michigan (Plate XII) that had been compiled by John F. Nellist from the notes of Leverett, Taylor, and numerous members of the State Geological Survey (Nellist, 1908). Part of this map is shown in Figure 6, and it remains the largest-scale depiction of the surface geology of the Lower (Southern) Peninsula of Michigan ever published. At this time, waterlaid moraines were not yet delineated on the map, and glacial lake shorelines were depicted but not labeled. Moraines composed of sand and gravel were differentiated by symbol from those dominated by clayey materials.

After Lane left the Michigan Geological Survey in 1909, R.C. Allen became the state geologist. Lane's aforementioned 1908 publication had been very popular, and its limited publication run was quickly exhausted, so in 1911, Allen engaged Leverett "… to adapt the results of a careful scientific study of the surface formations of the state to a distinctly utilitarian purpose" (Leverett, 1912, p. 12). The two publications resulting from this work contained 1:1,000,000 scale, color maps for the Upper (Northern) Peninsula (Leverett, 1911) and the Lower (Southern) Peninsula of Michigan (Leverett, 1912; Fig. 7 herein). In light of the popularity of Lane's (1908) report and the Nellist (1908) map it contained, Allen arranged to have numerous loose copies of Leverett's maps printed (Leverett, 1912, p. 15). For the first time, these maps differentiated by symbol between landlaid and waterlaid moraines. The legend text states that the composition of moraines can vary from very stony material to heavy clay with few stones. Glacial lake shorelines were depicted but not labeled on the Lower (Southern) Peninsula of Michigan map.

Eventually, after nearly 30 years of painstaking fieldwork and numerous delays within the USGS (Rieck and Winters, 1982), USGS Monograph 53, *The Pleistocene of Indiana and Michigan and the History of the Great Lakes*, was published (Leverett and Taylor, 1915). Leverett and Taylor had hoped to have their manuscript ready for publication by the early summer of 1910, but the final editing of the maps, illustrations, and text proved to be an arduous, time-consuming task. It was not until January 1914 that the manuscript was finally sent to the printer (Baclawski, 2013).

Plate 7 of Monograph 53 (Fig. 8) depicts the surface formations of the Lower (Southern) Peninsula of Michigan. Like the map that accompanied Leverett's 1912 publication, Plate 7 differentiates by symbol between landlaid and waterlaid moraines. Unlike the previous map, Plate 7 makes no mention in the legend

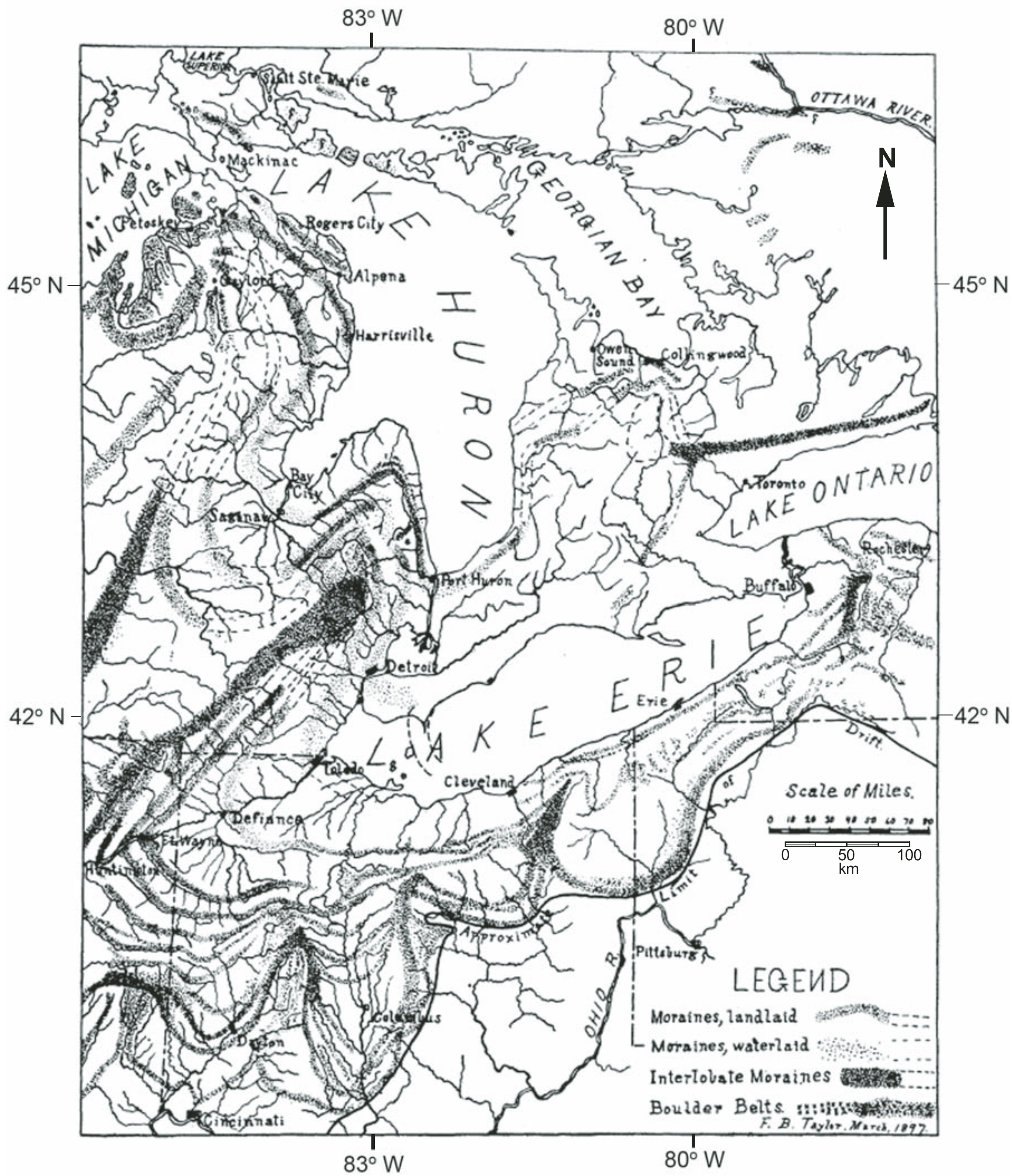

Figure 2. Map of recessional moraines in part of Michigan and Ohio, modified from Taylor (1897b).

about the composition of moraines. Glacial lake shorelines are shown on Plate 7, and, for the first time, many are labeled.

The collaborative and iterative nature of early glacial mapping efforts in Michigan becomes readily apparent when comparing the maps of Lane (1898; Fig. 3), Nellist (1908; Fig. 6), Leverett (1912; Fig. 7), and Leverett and Taylor (1914; Fig. 8). The same can be said for the maps of Russell (1907a), Leverett (1911; Fig. 4), and Leverett (1929; Fig. 5). Taken together, these maps represent the work of a team of extraordinarily dedicated geologists whose perseverance and great skill culminated in the publication of two masterful examples of early twentieth century cartography and field science (Leverett and Taylor, 1914; Leverett, 1929). That these maps came together with almost no topographic coverage is truly remarkable. The importance and significance of these maps, and the effort it took to produce them, cannot be overstated.

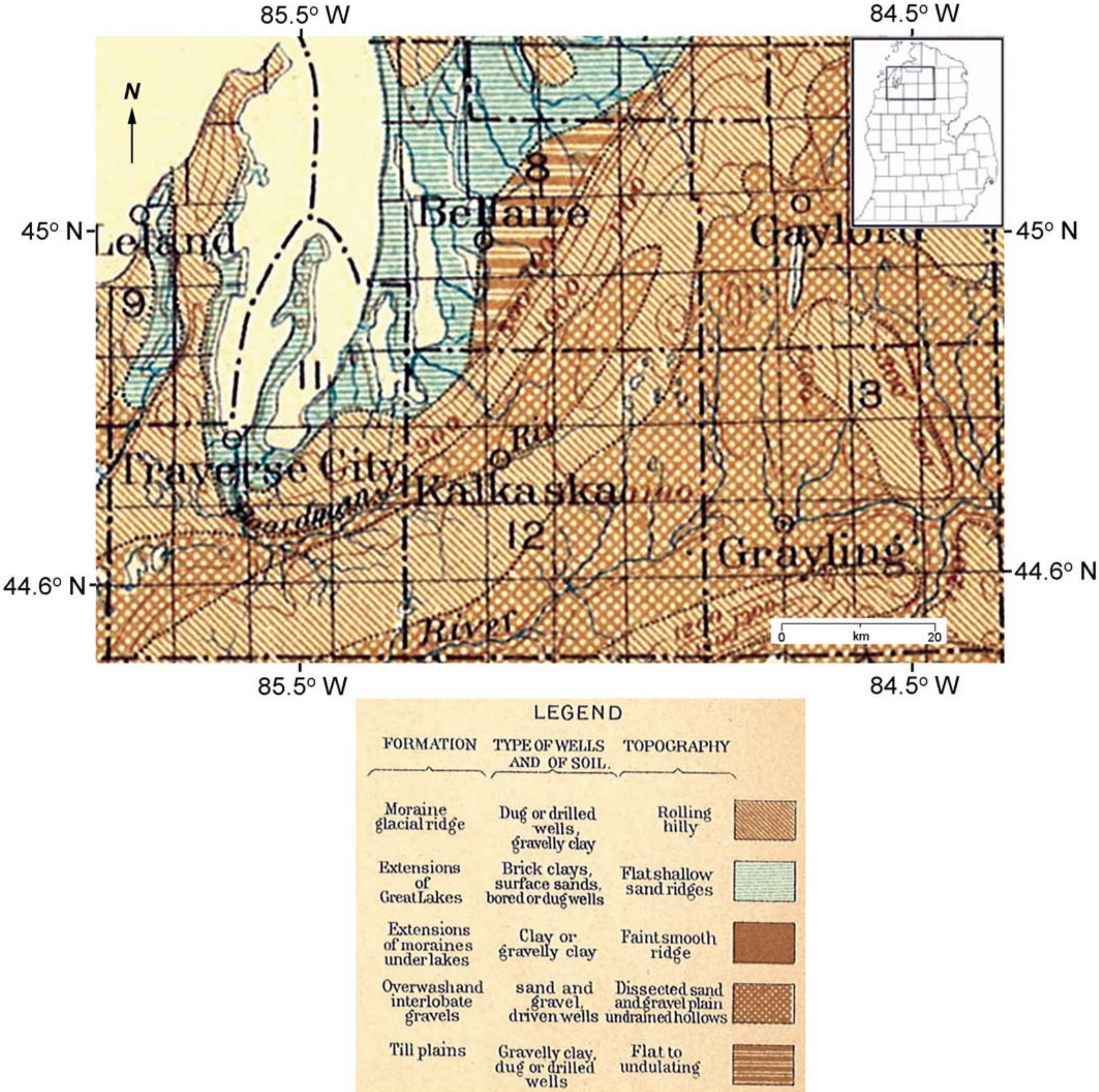

Figure 3. Pleistocene deposits in the northwestern part of the Lower (Southern) Peninsula of Michigan, modified from Lane (1898). The NE-SW–trending inner and outer Port Huron moraines (see Fig. 15) are shown from E of Bellaire to SW of Traverse City, Michigan.

Mapping Methods, Data, and Approaches

USGS Monograph 53 is organized into 25 chapters, but, notably, there is no methods section. In an earlier monograph, however, Leverett (1899, p. 4), provided insights into his mapping methods. He wrote that his fieldwork in an area began by mapping the moraines, using zigzag transects that allowed him to observe their breadth, crest position, and general surface features. He also investigated the stratigraphy of the sediments by studying exposures he could find, and evaluating thousands of water well records. Leverett provided even more details about his field methods in his article on "Field Methods in Glacial Geology," in which he noted that Chamberlin directed him to map "all moraines, outwash plains, lines of glacial drainage, eskers, kames, drumlins, and intermorainic till tracts …" and to study all

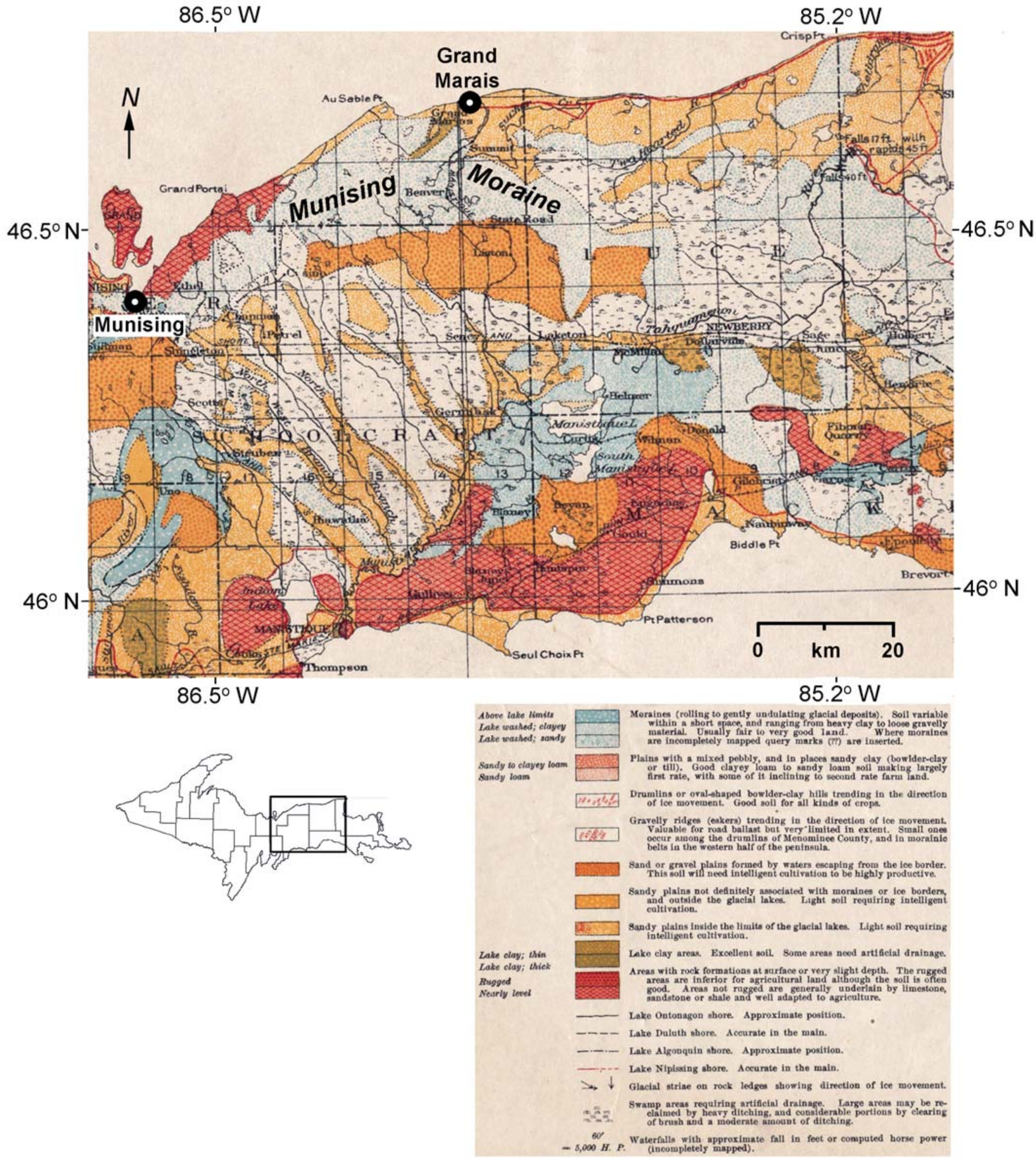

Figure 4. East-central portion of the first surficial geology map of the entire Upper (Northern) Peninsula of Michigan, modified from Leverett (1911). Note the distinction between landlaid and waterlaid moraines and the differentiation between the clayey and sandy composition of the waterlaid moraines.

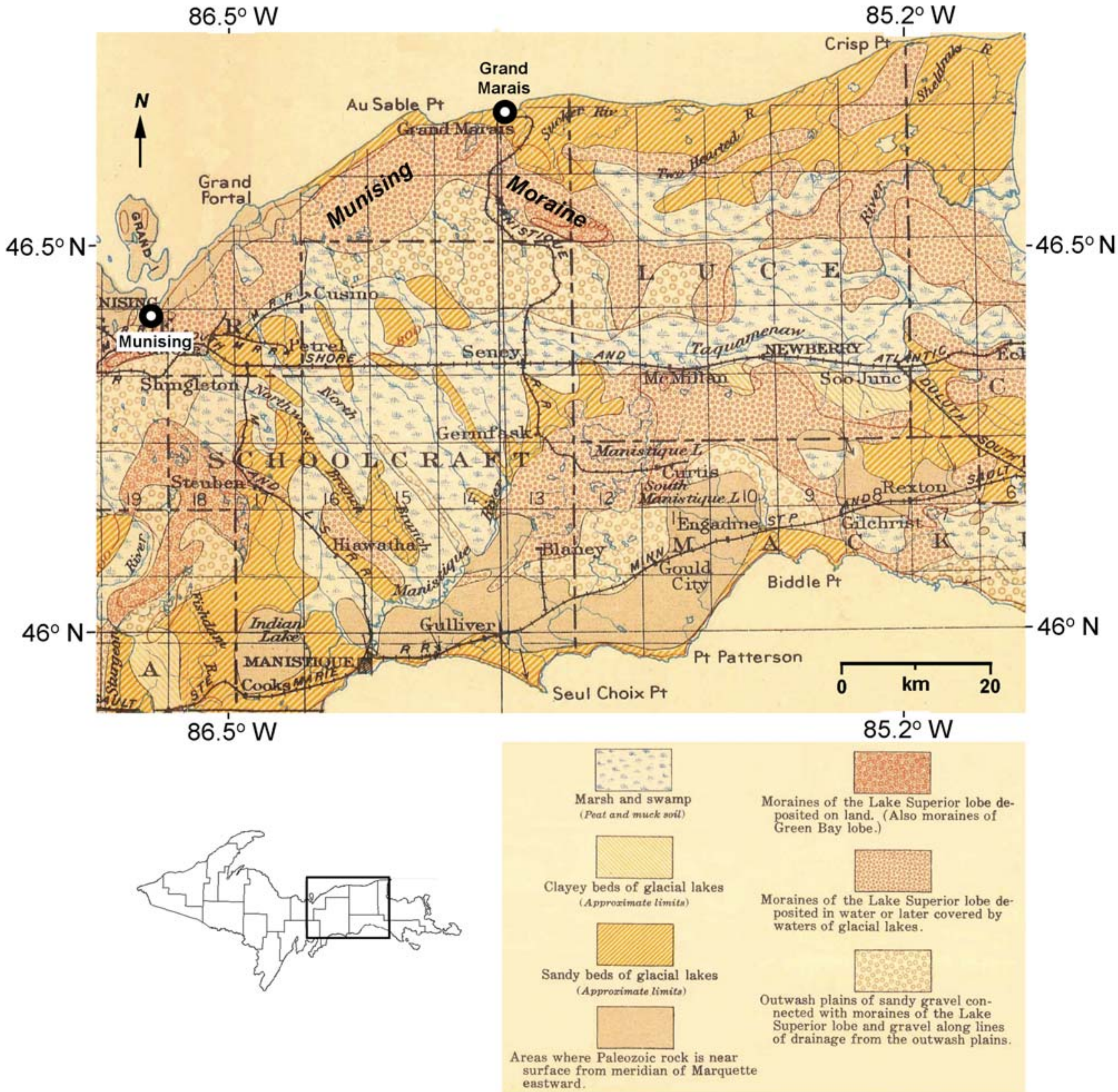

Figure 5. Extract from the *Map of the Surficial Deposits of the Lake Superior Region,* modified from Leverett (1929). Note the distinction between landlaid and waterlaid moraines with no differentiation between clayey or sandy composition.

available "natural and artificial exposures, of well records, and all available material bearing upon the succession of glacial formations" (Leverett, 1913, p. 583).

According to Rieck and Winters (1981), Leverett's field season sometimes began as early as April or May and concluded in November or December. He usually worked alone and frequently walked up to 20 or 30 mi (32 to 48 km) per day (Stanley, 1945). Leverett also traveled by horse and buggy or by saddle horse, sometimes covering nearly 50 mi (80 km) in a day (Rieck and Winters, 1981). Leverett's unit of field study appears to have been the survey township, likely because there were always General Land Office plat maps available. He noted, however, that important glacial features, such as raised beaches, eskers, drumlins, and kames, all "…must be followed at close range to insure [*sic*]

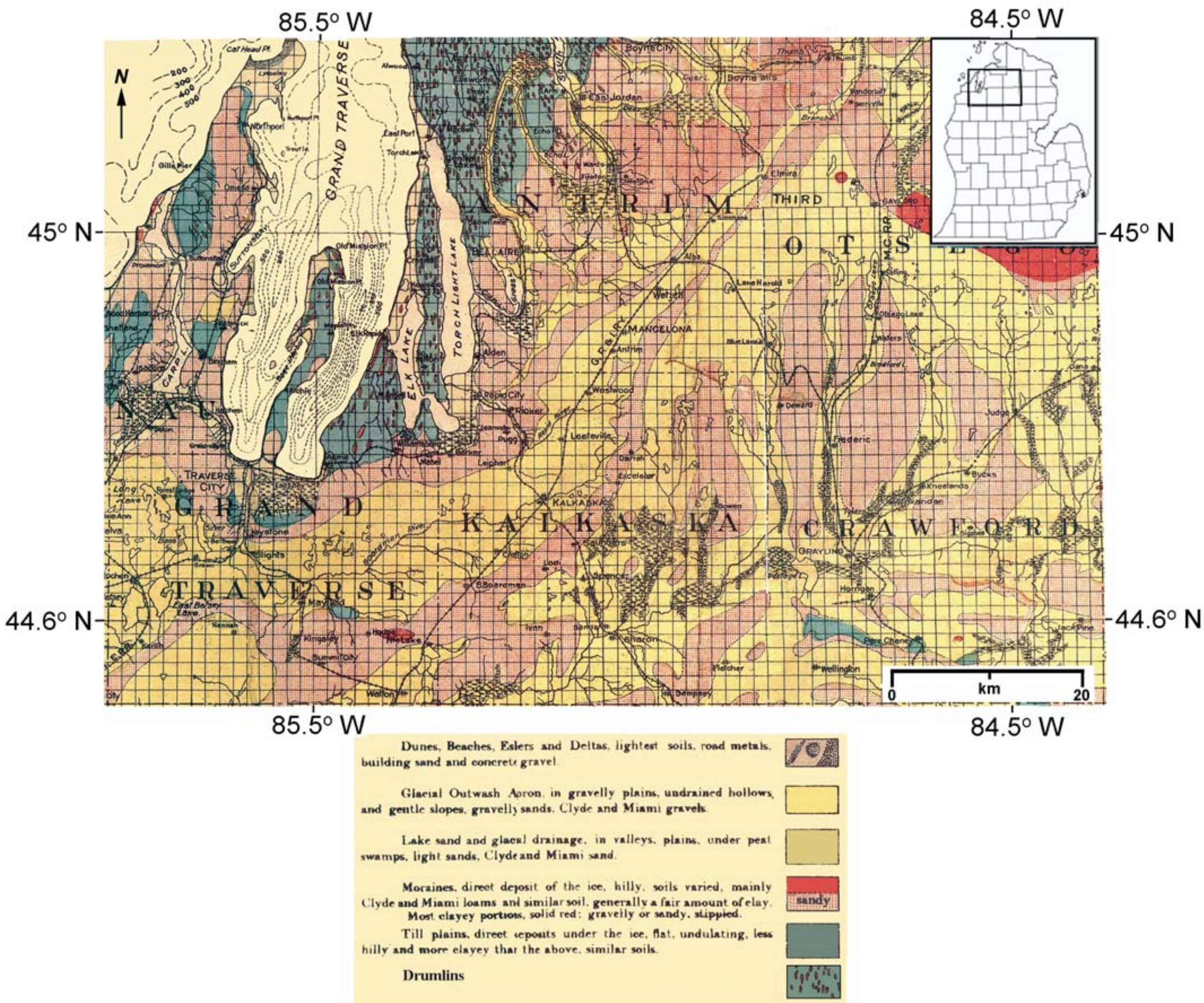

Figure 6. Extract from the *Surface (Pleistocene) Geology of Southern Michigan,* modified from Nellist (1908), Plate XII, Sheets 4 and 5. Note that most of the moraines in this part of Michigan are depicted as gravelly or sandy.

correct mapping" (Leverett, 1913, p. 585). Interestingly, geologic cross sections, diagrams, and maps are rare within the more than 300 field notebooks that Leverett filled (Rieck and Winters, 1981). The vast majority of his observations were recorded as written descriptions.

Nonetheless, we know that Leverett was always sketching some type of field map and that his field cartographic technique was very refined (Leverett, 1913, p. 586):

> On the field maps marginal references are frequently made to the notebooks which contain the principle geologic data, and as much data as can conveniently be placed on the map is entered there as well as in the notebooks.
>
> In the writer's practice mapping in the field is by a system of colors supplemented to some extent by conventions. The colors adopted have been such as to make strong topographic features stand out prominently, while plains are represented in duller colors.
>
> This system has been elaborated sufficiently to bring out drift structure as well as topography. For example, for topography a moraine is given a red color, an outwash gravel plain a brown color, and a till plain a blue color, while for structure a gravelly part of a moraine has a brown color rubbed over the red, while the clayey part has a blue color over the red.

Perhaps the most remarkable aspect of Leverett and Taylor's mapping technique is its overall accuracy, given that very few

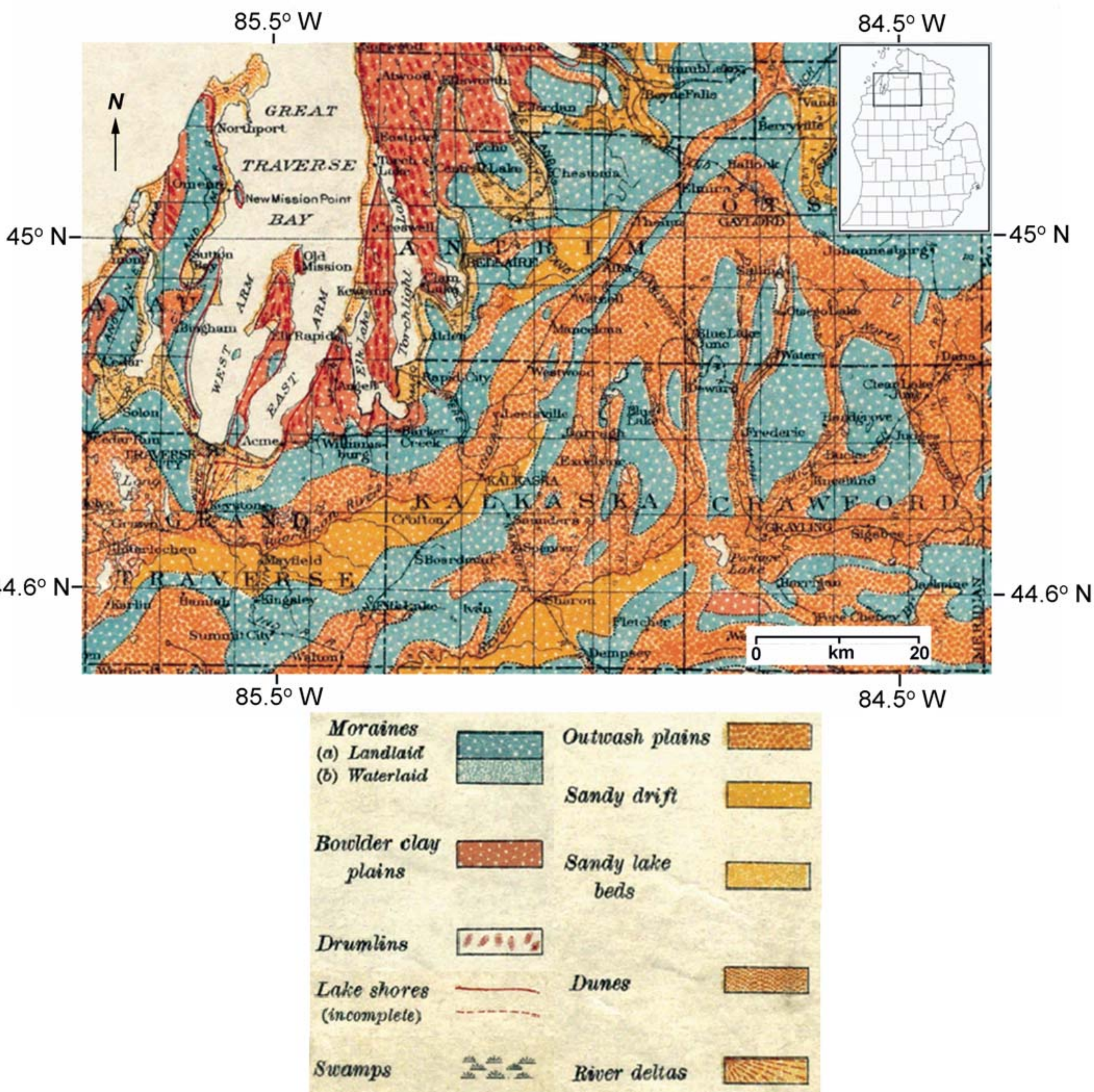

Figure 7. Extract from the *Map of the Surface Formations of the Southern Peninsula of Michigan,* modified from Leverett (1912). All of the moraines in this part of Michigan are depicted as landlaid, with no distinction between clayey or sandy composition.

topographic maps existed at the time. They commonly used large-scale, commercially produced plat maps or county road maps as their base maps. By this time, most survey sections were bounded or bisected by roads or wagon trails. Residential structures were also frequently depicted on these commercially produced maps. The roads, trails, and railroads not only provided easier access to the countryside, but they also provided key geolocational infrastructure that could be observed in the field. Without topographic maps showing the "lay of the land," correctly mapping the location and extent of landforms would have been nearly impossible without base maps showing streams, lakes, roads, and other structures for reference.

In the absence of topographic maps, Leverett and Taylor relied heavily on the engineering surveys of the numerous

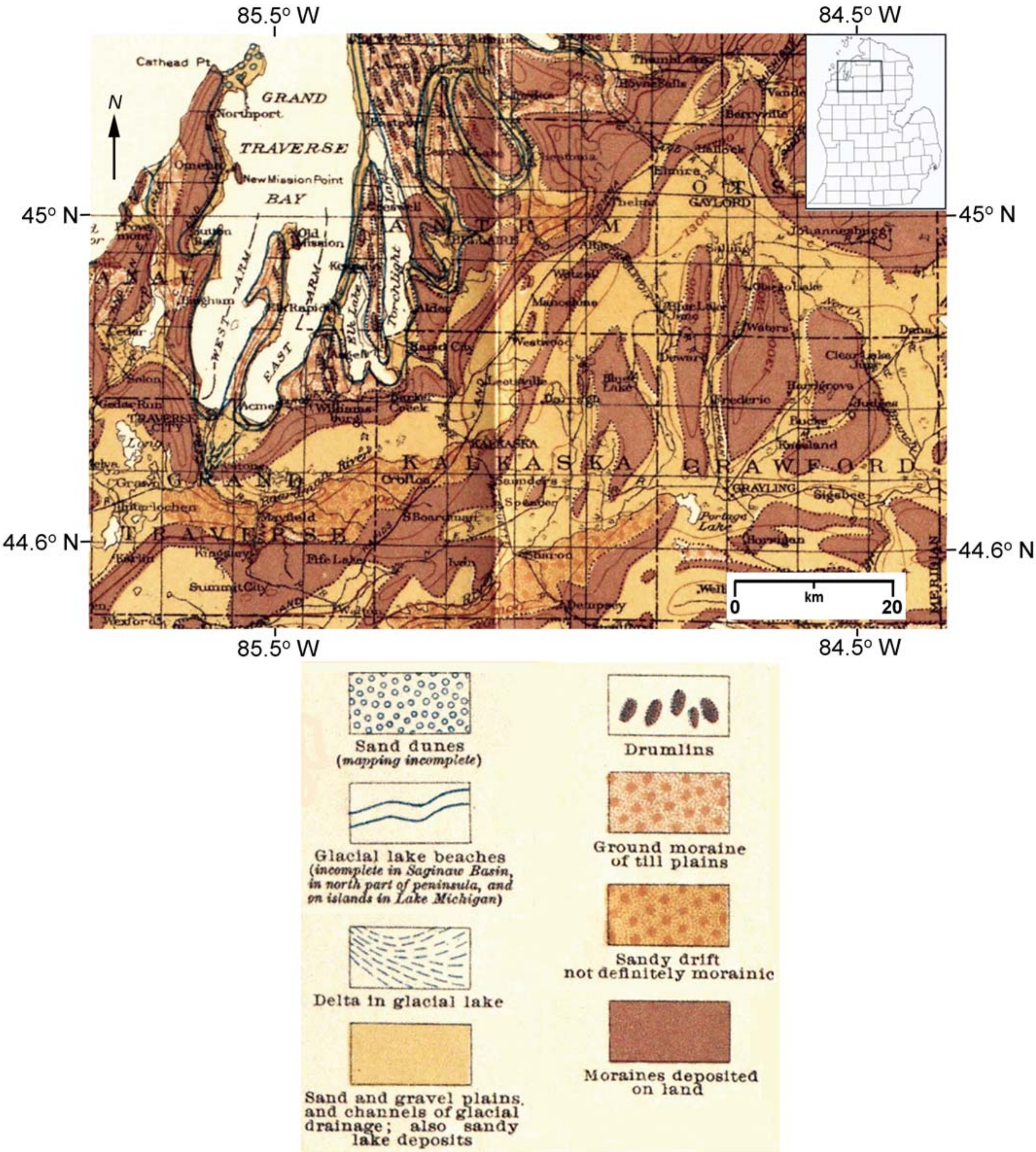

Figure 8. Extract from the *Glacial Map of the Southern Peninsula of Michigan,* modified from Plate 7 in Leverett and Taylor (1915). All of the moraines in this part of Michigan are depicted as landlaid, with no distinction between clayey or sandy composition.

railroads across the state and on their own aneroid barometers for elevation control. Most of the numerous train stations had an elevation benchmark that could be used to calibrate a barometer. Railroad survey records often recorded spot elevations at road and river crossings, which were also useful for calibration.

As mentioned previously, Leverett evaluated thousands of water well records before and during his mapping campaigns (Leverett, 1906, 1907). Much of his knowledge of what he called "drift structure" was derived from water well records, for example (Leverett and Taylor, 1915, p. 127):

> A well on Mr. Peterson's farm near the State line, in sec. 11, T. 28 N., R. 10 W., on a high part of the moraine, penetrated 168 feet of drift, of which the lower 8 feet was water-bearing sand and the remainder till. A neighbor's well 171 feet deep passed through 165 feet of till before striking water-bearing sand.

Emphasis on Morphology over Sediments

Chamberlin (1883, p. 311–312) described moraines as being composed of both "assorted and stratified material" as well as "… a confused commingling of clay, sand, gravel, and bowlders [*sic*] of the most pronounced type." Such a description runs contrary to the definition in common use today by some geologists, where moraines are ridge-like accumulations of unsorted, unstratified glacial till, deposited primarily by the direct action of glacier ice along its margin. The fact that Chamberlin had earlier studied and mapped in the Kettle Moraine region of Wisconsin (Chamberlin, 1878), an interlobate area, undoubtedly influenced his definition of a moraine. For him and those he influenced, moraine mapping involved the identification and classification of topographic form, with little regard to sediment composition. This was primarily a by-product of limited exposures and well data. Chamberlain's emphasis on morphology carried over to Leverett and Taylor. For example, Leverett's acceptance of stratified sediments as typical components of a moraine is clear in his description of Kalamazoo Moraine of the Lake Michigan Lobe (Leverett and Taylor, 1915, p. 177):

> Throughout the length of both ridges of the Kalamazoo system the drift is mainly assorted material of various grades of coarseness … the general prevalence of thick beds of sand and gravel is shown by numerous well records, supplemented by natural exposures near streams and on the edges of the basins of the small lakes.

For Chamberlin, Leverett, Taylor, and most of their contemporaries, what was important about moraines was that they had topographic relief, rendering them mappable at scales of convenience, that they formed at former ice margins of ice lobes, and that they exhibited crosscutting relationships with other landforms that were useful in establishing the relative geologic history. The nuances of depositional processes revealed by the sedimentology would remain understudied for the next 70 years.

Mapping by Helen Martin

Background

Helen Martin received degrees in geology and chemistry from the University of Michigan in 1908 (B.A.) and 1917 (M.S.), where she took courses from Frank Leverett on glacial geology. She was a true pioneer, as few women attended college in the early 1900s, and even fewer studied the Earth sciences.

Martin was employed by the Michigan Geological Survey from 1917 to 1958, working as an economic geologist, editor, director of the Land Economic Survey, compiler of geological maps, and outreach lecturer. Her most well-known contributions were the compilation of *The Centennial Geological Map of the Northern Peninsula of Michigan* and *The Centennial Geological Map of the Southern Peninsula of Michigan* (Martin, 1936), as well as the surface formations maps of Michigan (Martin, 1955, 1957). In 1957 and 1958, just before she retired, Martin published a series of open-file reports, aimed primarily at lay audiences, which described the glacial geology of 15 counties in southern Michigan.

Mapping Methods, Data, and Approaches

F.W. Terwilleger, a student of Martin's contemporary, Stannard Bergquist, provided useful context for Martin's mapping effort. Leverett, he says (1952, p. 2)

> … mapped on a broad scale, and did not intend to show the detail which can be obtained when mapping on a county basis, and with topographic map control. To fill the need for more detailed work, county mapping has been carried on for some years by Miss Helen M. Martin of the Geological Survey Division of the Department of Conservation, and Dr. S.G. Bergquist, head of the Department of Geology and Geography at Michigan State College. The maps thus prepared are being transferred to a state base on a scale of 4 miles to the inch. The finished map as printed will be on a scale of 8 miles to the inch.

The printed maps that Terwilliger referred to were those compiled by Martin (1955, 1957). There are no published descriptions of the mapping methods used by Martin or Bergquist. However, since Martin studied under Leverett, and Bergquist received his Ph.D. in geology from the University of Michigan in 1933 (shortly after Leverett retired), it is reasonable to assume that both Martin and Bergquist employed techniques similar to those that Leverett had developed. As circumstantial evidence supporting this assumption, Terwilliger (1952, p. 3), who was trained by Bergquist, wrote:

> The glacial mapping was done mainly from observations along the roads, with only short traverses on foot, either where roads were impassable or where it was desired to examine certain features more

closely. The county has a very good net of section-line roads, and is covered by a soils map and topographic quadrangles.

Leverett's map (1924) was used as a guide. The soils map (Wildermuth et al., 1926) was used in connection with test borings, gravel pits, excavations, road cuts, and other openings in the ground to determine the character of the drift. The glacial features were identified by local observation of topography and soil types. The topographic sheets were used extensively in the field to determine elevations and relief, as well as to give a better overall view of certain of the larger features.

In compiling the *Map of Surface Formations of the Southern Peninsula of Michigan*, Martin (1955) took advantage of all available published information (e.g., Leverett and Russell, 1908; Leverett and Taylor, 1915; Sherzer, 1917; Pringle, 1937; Terwilliger, 1952) and one unpublished thesis (Stewart, 1948). However, the majority of her map compilation for the Lower (Southern) Peninsula of Michigan relied on Leverett's field notes and manuscript maps, as originally assembled for USGS Monograph 53 (Leverett and Taylor, 1915), covering the central third of the peninsula. Compilation sources for the northern third of the lower (southern) peninsula included manuscript maps of various counties by Martin and Bergquist. Compilation sources for the southern third of the lower (southern) peninsula included manuscript maps from Leverett drawn on 15 min topographic quadrangles, as well as manuscript maps for various counties by Martin and Bergquist.

In Michigan's Upper (Northern) Peninsula, Martin (1957) relied on three major sources of information. For most of the western part of the upper (northern) peninsula, as well as Mackinac County, she consulted Leverett's 1929 USGS Professional Paper, as well as his field notebooks. For Alger, Schoolcraft, and Luce Counties, she relied on Bergquist's (1936) dissertation, which was published by the Michigan Geological Survey. For Iron County, Martin relied on the unpublished maps and field notes of the Michigan Land Economic Survey. Her sources for Menominee and Chippewa Counties were the unpublished maps and field notebooks of W.C. Ver Wiebe of the Michigan Land Economic Survey.

Correlations and Interpretations

Martin's map (1955) incorporated mapping by Terwilliger (1952) in southwestern Michigan, who had apparently accepted Leverett's description of the Kalamazoo Moraine as being composed mainly of sandy and gravelly sediments. He also stated (1952, p. 5) that numerous water wells in the moraine that were 350–450 ft (107–137 m) deep were set in predominantly sand and gravel materials. His map of the glacial geology of Van Buren County does not differentiate between moraines composed of unsorted till and those composed of sorted sand and gravel.

Martin's 1955 map (Fig. 9) was published at a larger scale (1:500,000) than Plate 7 (1:1,000,000) of USGS Monograph 53 (Leverett and Taylor, 1915), but the surface formations it depicts are very similar. Like Leverett's 1911 and 1915 maps, Martin differentiated between landlaid and waterlaid moraines. Unlike the map accompanying Leverett's 1912 publication (but following the precedent of Plate 7 of USGS Monograph 53), Martin made no mention in her legend about moraine composition. Both maps by Martin (1955, 1957), however, depicted and labeled selected glacial lake shorelines. Indeed, Martin's (1955) larger-scale map depicts the various glacial lake shorelines with much greater detail than did USGS Monograph 53, Plate 7 (Leverett and Taylor, 1915). These differences are especially obvious in the central portion of the Saginaw Lowlands.

Because the glacial features of much of the Lower (Southern) Peninsula of Michigan had been recompiled on topographic base maps by the time Martin compiled her map, it is not surprising that some features would be depicted differently when compared to Plate 7. For example, Plate 7 shows a narrow, landlaid moraine trending NE-SW across T9N, R6E in northern Genesee County, which then turns south along the east side of T8N, R5E, ending just before the Flint River. This moraine is shown to continue WSW on the south side of the river in the northeastern corner of T7N, R5E, trending past the village of Lennon near the Shiawassee-Genesee County line. On Martin's (1955) map, however, most of this moraine segment was mapped as till plain. These types of minor revisions are quite common in Martin's maps, but the majority of her mapped polygons conform closely to Leverett and Taylor's earlier mapping.

Significance and Persistence

As discussed previously, Chamberlin had focused on delineating recessional moraines, an approach that developed into a conceptual framework known as "normal retreat." As glacial mapping progressed in New England, where recessional moraines are not readily apparent, it became obvious to many field geologists that the "normal retreat" model of the Midwest was inappropriate in New England. Richard Foster Flint (1929) was one of the early and forceful proponents of the regional ice stagnation concept, based on his mapping work in Connecticut. Taylor was strongly opposed to the regional stagnation concept and wrote (1931, p. 334) that "… features [in New England] show oscillating retreat as clearly as they do in the [Great Lakes region]." With that, the applicability of the stagnant-zone retreat model to help in deciphering some of the problematic glacial terrain in Michigan was forestalled. Only much later would Rieck (1976) use ice stagnation to explain portions of the interlobate landscape of eastern Jackson and western Washtenaw Counties in southeastern Lower Michigan.

For more than 25 years, the surface formation maps compiled by Martin (1955, 1957) were the best available, large-area depictions of the glacial features of Michigan. For many mid-twentieth and later twentieth century students of glacial geology in Michigan, Martin's maps were their constant companions. As mentioned previously, there were a handful of county-scale or larger glacial maps, often embedded in graduate theses, dissertations, or USGS publications (e.g., Shah, 1971; Twenter and Knutilla, 1972; Burgis, 1977), but for most investigators, Martin's (1955, 1957) maps were the starting point. Though Martin

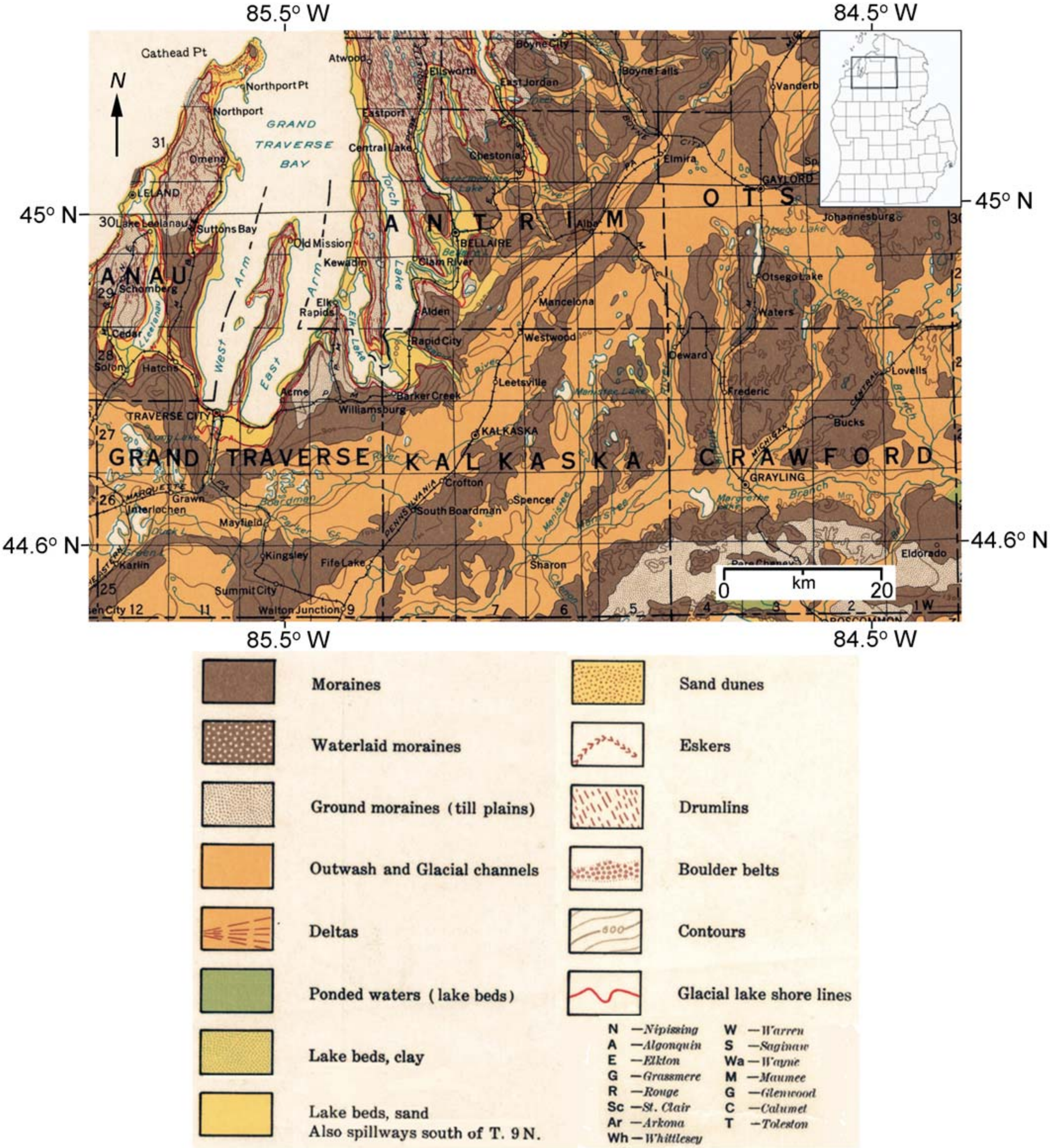

Figure 9. Extract from the *Map of the Surface Formations of the Southern Peninsula of Michigan,* modified from Martin (1955). All of the moraines in this part of Michigan are depicted as landlaid, with no distinction between clayey or sandy composition.

acknowledged that these maps were essentially recompilations of earlier maps by Leverett and Taylor, this situation was not always known or appreciated by users.

Mapping by William Farrand

Background

With the support of the Michigan Geological Survey and the USGS, William R. Farrand published two Quaternary geology maps of Michigan in 1982, one for the lower (southern) peninsula and one for the upper (northern) peninsula (Farrand, 1982a, 1982b). In 1998, the Michigan Natural Features Inventory and the Michigan Department of Natural Resources digitized hard copy versions of these maps, projected them into the Michigan GeoRef coordinate space (the geospatial standard in Michigan), and made them publically available for use in geographic information systems (GIS).

Farrand was a geology faculty member at the University of Michigan, and his early research focused on the glacial history of northern Michigan and Lake Superior (Farrand, 1960, 1962, 1969; Farrand and Drexler, 1985). He was also among the first to apply radiocarbon dating techniques to document the timing of glacial events in the region (Farrand et al., 1969).

Mapping Methods, Data, and Approaches

By 1980, virtually every county in the Lower (Southern) Peninsula of Michigan had a large-scale soil survey. Each of these published surveys included a general soil map, which showed the distribution of soil associations across the county. Farrand combined these soil data with landform outlines largely borrowed from Martin's maps (1955, 1957) to create new surficial geology maps focused on surficial sediments rather than morphology (Fig. 10). These data were supplemented by two dissertations that covered the northernmost portions of Lower (Southern) Peninsula of Michigan (Melhorn, 1954; Burgis, 1977), one published subcounty study of the Ubly-Tyre Outlet in south-central Huron County (Drake, 1980), and two published studies in Wayne and Monroe Counties (Mazola, 1969, 1970). In the Upper (Northern) Peninsula of Michigan, the soils data and mapping units from Martin were supplemented with one dissertation (Drexler, 1981) and one research article (Black, 1969).

Correlation and Interpretations

Unlike earlier maps, Farrand (1982a, 1982b) provided a detailed map legend. He recognized 24 principal map units that included generic and genetic terminology as applied to sediments and landforms. For example, end moraines, eskers, drumlins, shorelines, and sinkholes (genetic landform terms) were included as mapping units, but outwash plains (also a genetic landform term) were not, and these were instead listed as "glacial outwash sand and gravel" (a genetic sediment term). Significantly, Farrand included the category "ice-contact outwash sand and gravel," a mapping unit he used sparingly. New mapping reveals this unit is extensive in interlobate areas and northern parts of the state.

Farrand's attempt to simplify the various mapping units sometimes led to discrepancies. For example, the category "end moraines of fine-textured till" was defined as nonsorted glacial debris occurring in narrow linear belts of "hummocky relief." Both the waterlaid Bay City and Port Huron moraines in the central Saginaw Lowlands were mapped as members of this class, but neither express hummocky relief. Another issue with Farrand's (1982a) map occurs in the northwestern part of southern Michigan, where the Inner and Outer Port Huron moraines are classified as "end moraines of coarse-textured till." Blewett (1991) established that these ice-marginal features are composed of sorted glaciofluvial sediments (see later herein) and better resemble kame moraines or "heads of outwash." The same can be said for the Kalamazoo moraine farther south. Using Farrand's map units, these features would be better categorized as "ice-contact outwash sand and gravel," except with well-sorted and well-stratified glaciofluvial sediments, rather than poorly sorted and poorly stratified deposits as listed in Farrand's legend.

Significance and Persistence

Despite more than 30 years since their initial publication, Farrand's maps remain the most recent statewide depictions of glacial features in Michigan. Although the incorporation of soils data produced more useful maps, Farrand incorporated little new data or interpretations and retained nearly all of the basic outlines of the maps by Martin (1955, 1957), which were based almost entirely on the maps of Leverett and Taylor (1914) and Leverett (1929). As one State of Michigan scientist once said to us, "We make decisions every day based on this map," and yet, the polygons and interpretations on the map were largely drawn almost 100 years ago.

Recent Advances in Mapping, Interpretation, and Geotechnology

Mapping and Interpretation

With the publication of Farrand's statewide surficial geology maps, the third (and current) chapter in the history of glacial mapping in Michigan began. This chapter is best characterized by the adoption of a wide variety of digital data within a GIS environment, based largely on Farrand's polygons. Although no statewide maps of surficial geology have been produced since those of Farrand (with the *Quaternary Geologic Atlas of the United States* being an important exception [U.S. Geological Survey, 2013]), advances in technology and data (both in type and in quality) have done much to foster better and more accurate mapping of selected subregions in the state. Facilitating this effort is a much-improved understanding of glacial processes, particularly with respect to ice stagnation and the formation of related features, such as tunnel channels and other landforms (Kehew et al., 1999, 2005; Fisher and Taylor, 2002). Work on eolian systems and landforms also blossomed during this time, as researchers became increasingly interested in Michigan's

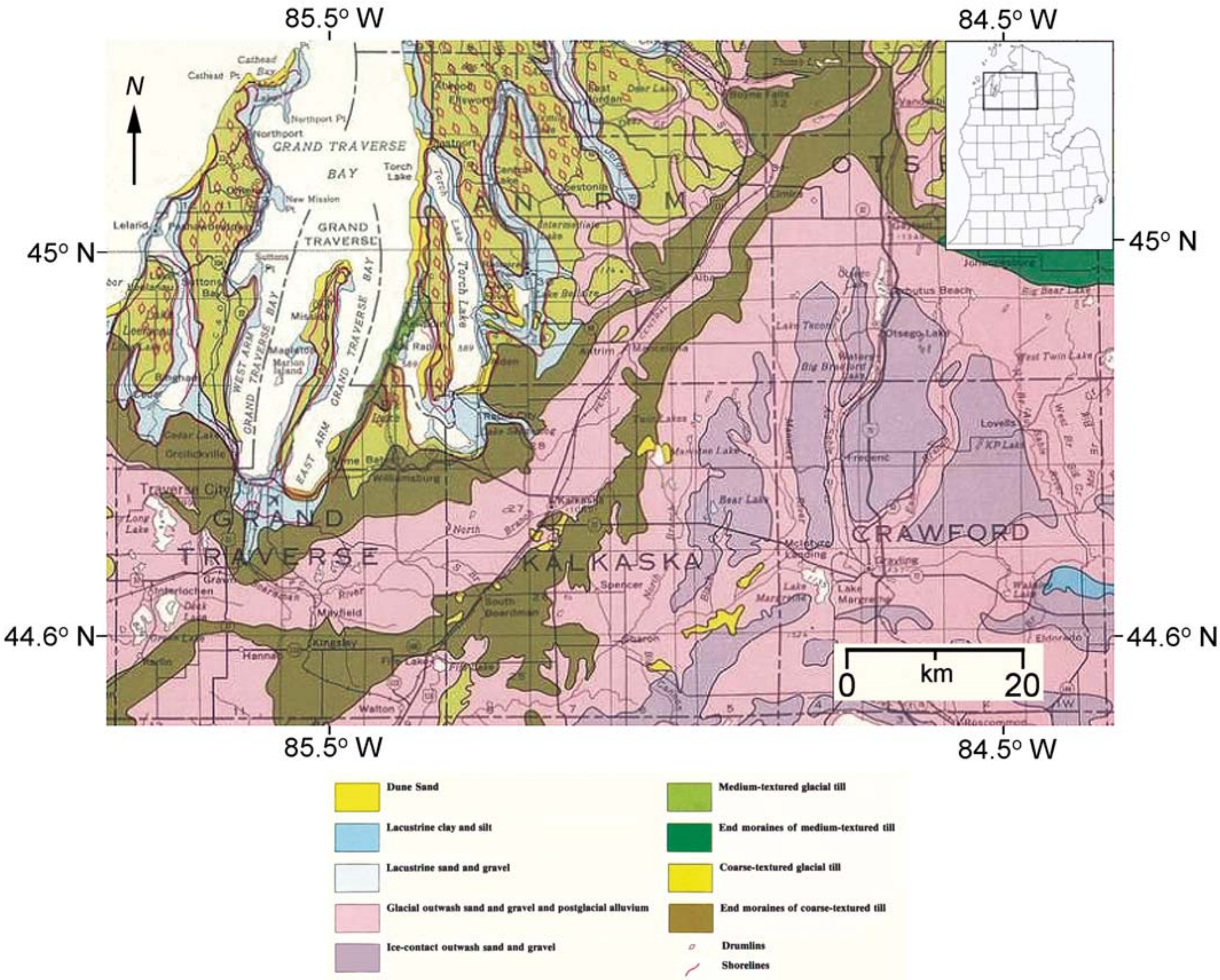

Figure 10. Extract from the map of the *Quaternary Geology of Southern Michigan,* modified from Farrand (1982a). Note that the NE-SW–trending inner and outer Port Huron moraines are mapped as “End moraines of coarse-textured till,” but the Grayling Fingers interlobate moraine complex (see Fig. 12) is mapped as “Ice-contact outwash sand and gravel.”

postglacial landscape. Much of this newer work involved university researchers and their students, as the Michigan Geological Survey labored under a difficult budgetary climate.

In 1997, the USGS teamed with several state surveys to create the Great Lakes Geologic Mapping Coalition (Berg et al., 2016). The original state survey members included Illinois, Indiana, Michigan, and Ohio, joined later in 2008 by Minnesota, New York, Pennsylvania, and Wisconsin, and in 2012, by Ontario, Canada. By integrating their expertise and resources, the coalition was better able to address geologic mapping issues than any one state or provincial survey alone. Because the eight states and Ontario share similar geology and common environmental issues, a partnership of this kind seemed logical. The mapping goals of the coalition focus on improving the understanding of land and water resources to inform sound, unbiased, and cost-effective land-use decisions. The program emphasizes detailed geologic map products, typically at the 7.5 min quadrangle-map scale of 1:24,000. Products include both three-dimensional (3-D) and traditional surficial geologic maps. The emphasis on geologic mapping from the surface down to the bedrock, including genetic interpretations of sediments, sets this effort apart from previous mapping efforts. Detailed digital geologic maps and 3-D models can be managed and updated as new data or new interpretations of old data become available as “living maps.”

The STATEMAP program and National Geologic Database (Soller and Stamm, 2014) complement the coalition’s work. The STATEMAP program is competitive, and researchers must match the funding contributed by the federal government. Typically, STATEMAP projects are undertaken either by various university researchers and their students or by state geological survey personnel.

As of 2016, these various mapping programs have produced 171 finished quadrangles for the State of Michigan. Of these, the coalition has produced 25 quadrangles, STATEMAP has produced 111 quadrangles, and EDMAP has produced 35 quadrangles (Kincare, 2016, personal commun.; numbers are approximate). While impressive, these numbers are only 12% of the 1319 1:24,000/1:25,000 topographic quadrangles covering the state of Michigan. According to Alan Kehew of the Michigan Geological Survey (2017, personal commun.), 1:24,000 scale county maps have been completed for St. Joseph, Barry, Calhoun, and parts of Allegan and Cass Counties. Light detection and ranging (LiDAR) data were available only for Calhoun County. The USGS has mapped Berrien County. This situation makes the prospects of compiling a statewide map based exclusively on glacial mapping of individual quadrangles exceedingly unlikely over the next several decades.

Better Data and Technologies

The widespread availability of high-quality, digital, topographic data has been critical to all modern mapping efforts (Florinsky, 2012). The USGS National Elevation Data set (NED; Gesch et al., 2002) first made 30-m-resolution digital elevation models (DEMs) available for Michigan in 1999, and 10-m-resolution DEMs became available later in 2003. DEMs and terrain analysis methods enable mappers and researchers to find and observe landforms that previously had gone undetected, to better analyze their spatial relationships, and to calculate their morphometric properties (Florinsky, 2012). Today, the 3D Elevation Program (3DEP) initiative is now renewing the NED by modernizing the way elevation data are collected, with LiDAR technology (Sugarbaker et al., 2014). Current LiDAR systems can determine elevations along a forest floor by recording reflected pulses that return through gaps in the forest canopy. Such systems typically produce elevation data with 30–60 cm horizontal and ±15 cm vertical accuracies. LiDAR data are available today in ~20 southern Michigan counties. In these areas, previously undocumented dune fields have been shown to be especially numerous, spawning a surge of related work (Arbogast et al., 2002a, 2002b, 2004, 2015; Arbogast and Loope, 1999; Hansen et al., 2010; Loope et al., 2004, 2012). Many "moraines" mapped by Leverett and Taylor (1915) were reinterpreted as heads of outwash, whereas still others, shown on all previous generations of maps, were nowhere to be found. Kettle chains, tunnel channels, and deltas are more common than the earlier mapping suggested, but some of these discoveries were only feasible due to LiDAR's high resolution. Thus, there is much to learn, fostering a new era of mapping from a desktop. Examples include land system maps (Kehew et al., 2012a) and GIS databases, which are becoming increasingly supported by a wide array of subsurface geophysical data.

By the early 2000s, the soils of all but a few small areas in Michigan had been mapped at the county level by the Natural Resources Conservation Service (NRCS) and converted to digital form. These maps assisted in a number of mapping efforts, of which the best example is perhaps the Michigan statewide physiographic map (Schaetzl et al., 2013), now hosted by the Michigan Geological Survey (http://mgs.geology.wmich.edu/flexviewers/physiography/). In general, soil maps have been shown to be important tools for determining the spatial patterns of parent materials in places where the genesis of the parent material was clearly understood. For example, in the northern part of the Lower (Southern) Peninsula of Michigan, the Nester soil series is developed in till. Using GIS reclassification, patches of Nester soils can then be mapped as till at the surface. Similarly, Bowers soils are formed in loamy lacustrine sediments. This approach—using soil maps as detailed surficial geology maps—enabled Schaetzl et al. (2000) to complete detailed glacial mapping and landscape analyses in both the northeastern and north-central portions of the Lower (Southern) Peninsula of Michigan (Schaetzl et al., 2000; Schaetzl and Weisenborn, 2004). For some soil series, however, the published series description does not provide interpretation of parent material genesis (e.g., loamy sediment), which may be determined by subsequent fieldwork. Nowhere is this better shown than in the western portions of the Upper (Northern) Peninsula of Michigan, where Luehmann et al. (2013) and Schaetzl and Luehmann (2013) determined that the "loamy sediments" in many of the upland soils is loess, often mixed with sandy glacial sediment below (see also Schaetzl and Loope, 2008). Last, derivatives of soil data, particularly the long-term wetness of soils as determined by the wetness index (Schaetzl et al., 2009), also have been shown to be highly useful in mapping efforts. All these techniques show the efficacy of combining multiple digital data sets within a GIS when analyzing and mapping surficial sediments and landforms.

Expansion of numerical dating technologies, such as optically stimulated luminescence (OSL) dating, has added chronologic control to various landforms and landscapes. OSL dating is especially applicable to sediments like dune sand and loess, because this method determines the last time that quartz or feldspar in the sediment was exposed to sunlight, and it does not rely on biogenic carbonaceous material as is needed for radiocarbon dating. Most of the OSL dating work in Michigan and nearby states has been on dunes (Arbogast and Loope, 1999; Hansen et al., 2010; Loope et al., 2012; Arbogast et al., 2015), although successful applications of OSL dating of outwash (Schaetzl and Forman, 2008), lacustrine sands (Attig et al., 2011; Carson et al., 2012) and deltaic sands (Schaetzl et al., 2017) widen the possibilities for future work. In addition, Be^{10} dating shows great promise for constraining the timing of regional glacial events (Ullman et al., 2015).

Due to funding constraints, it seems reasonable to expect that a statewide or state-funded mapping effort is still years away. Instead, high-quality mapping of smaller areas and portions of counties appears to be the modus operandi for the near future.

Improved tools and data sets will enable researchers to map such areas in detail at the surface and (increasingly so) in the subsurface. Digital water well data, which are widely available in Michigan, as well as data derived from dedicated drilling efforts, will do much to enhance our understanding of the subsurface. LiDAR data will increase the resolution of the topographic surface by tenfold or more, facilitating the identification of landforms so small that they could be easily missed, even from the ground. Soil data will also become better, as "edge-match" issues at county boundaries, an ongoing effort by NRCS, are resolved. Most important, interpretations of glacial processes will continue to improve, so that the various types of data can be artfully blended into increasingly better models of deglaciation.

Multiple new technologies are transforming the kinds and amounts of high-quality data that can be collected from small areas. Many rely on Global Navigation Satellite Systems (GNSS), including the U.S. global positioning system (GPS), which allows users to collect precise time, location, and elevation data along with other field observations and measurements. Schaetzl et al. (2002) and Drzyzga (2007), for example, used survey-grade GNSS devices and careful mission planning to survey paleoshoreline sites and record site descriptors and data taken from soil cores. Blewett et al. (2014) used the same protocol to georeference paleoshorelines, OSL data, and soil sampling sites, and the nodes and vertices along 30 km of ground-penetrating radar (GPR) transects.

Over the last decade, aerial image acquisition technology has rapidly evolved to collect direct-digital imagery with 1 m or finer pixel resolution that is usually delivered as an orthorectified mosaic. Such mosaics, however, do not allow stereo inspection. Instead, the 3-D topography insights are now derived from inspection and analysis of DEMs, as discussed earlier herein. Ground photographs have been a staple in geologic reports since the early 1900s. Today, mobile devices that couple high-resolution cameras with GNSS technology and an inertial measurement unit (IMU) can establish and document photo stations quickly and easily, which fosters repeat photography. The date, time, position, and view angles along and above the local horizon can be systematically imprinted on each image or embedded in the header of each image file. Aggregation platforms (e.g., the Open Data Kit by the Change Group, 2015) can be used to build and deploy a data collection form across multiple mobile devices and can ensure that standardized data are collected by device users. They also ensure that all collected data are uploaded to and conflated in a central database. Aggregated digital field data (and metadata) can be ready for use in a GIS environment before the field crew returns home with their field notebooks.

The use of small unmanned aircraft system technology (sUAS or drones) is one of the latest innovations in geologic mapping (Evans et al., 2016; Jordan, 2015). A typical sUAS is a robotic device that weighs less than 25 kg and is controlled remotely by radio transmitter. Most are equipped to carry a camera or a LiDAR device. When equipped with an onboard GNSS-guidance system, a sUAS can be used to collect oblique videos and photographs (Fig. 11), or vertical stereo-pairs that can be geoprocessed to create high-resolution terrain models. Whereas Leverett and Taylor often had the advantage of observing landscapes after they were denuded of their presettlement vegetation covers, today's geologists can get first-person views of landforms and hazards from 100 m above ground and from multiple new vantage points. One wonders how much more difficult Leverett and Taylor's mapping might have been had they had this much detail.

One of the most significant innovations in geologic mapping and research will occur after 2022 when the U.S. National Geodetic Survey (NGS) adopts a new ellipsoid and a new temporal geoid model for North America (National Geodetic Survey, 2016). The new spatial referencing systems based on these models will rely primarily on GNSS technology and initiate a new era of time-tracked coordinates and elevations, which will support improved analyses of glacial isostatic readjustments in the Great Lakes region. As noted already, Leverett relied heavily on aneroid barometers to determine elevations marked along railroads. Aneroid barometer technology fostered "hasty" surveys (Livingston, 1902). Charles Davis, a contemporary of Leverett and Taylor who also worked under Alfred C. Lane, remarked that "no

Figure 11. Oblique aerial photograph (taken 3 August 2015) from above a sequence of relict beaches on the slopes of Manitoulin Island, south of Little Current, Ontario, Canada. The beaches (numbered) belong to the "Algonquin 'Upper Group'" (Lewis, 1968).

pretense of a high degree of accuracy is made for the method, but the map produced … is sufficiently accurate to see … where the rougher parts of the county lie" (Davis, 1909, p. 138). The limits of equipment and datum precision at the turn of the twentieth century were enough to mask the ongoing process of differential vertical movement across the Great Lakes region (Coordinating Committee on Great Lakes, 1977; Clark et al., 1994; Mainville and Craymer, 2005). Had Leverett and Taylor been able to detect vertical movement at locations south of the Fenelon Falls outlet in Ontario, they might have dismissed Goldthwait's (1908, 1910) hinge metaphor and rigid model of crustal movement.

CASE STUDIES

The problems and complexities of research and glacial mapping in Michigan are illustrated next by briefly examining several recent case studies.

Grayling Fingers

The Grayling Fingers (Schaetzl and Weisenborn, 2004) are a large, upland landform assemblage in the north-central portion of the Lower (Southern) Peninsula of Michigan, formed in an area of exceptionally thick glacial and glaciofluvial sediment (Fig. 12). Together, the six plateau-like "fingers" form a triangular area ~43 km wide and 40 km in N-S extent, separated by dry, sandy, flat-floored valleys ("finger valleys"), presumably cut by glacial meltwater. Most finger valleys are 1.5–3.5 km wide and incised between 30 and 60 m below the uplands. The entire sediment assemblage—both uplands and valleys—slopes gradually to the south.

The geomorphic evolution of the Grayling Fingers region was only recently studied in detail. Previously, these uplands were assumed to be moraines. Leverett and Taylor (1915) acknowledged that the Grayling Fingers were part of a large

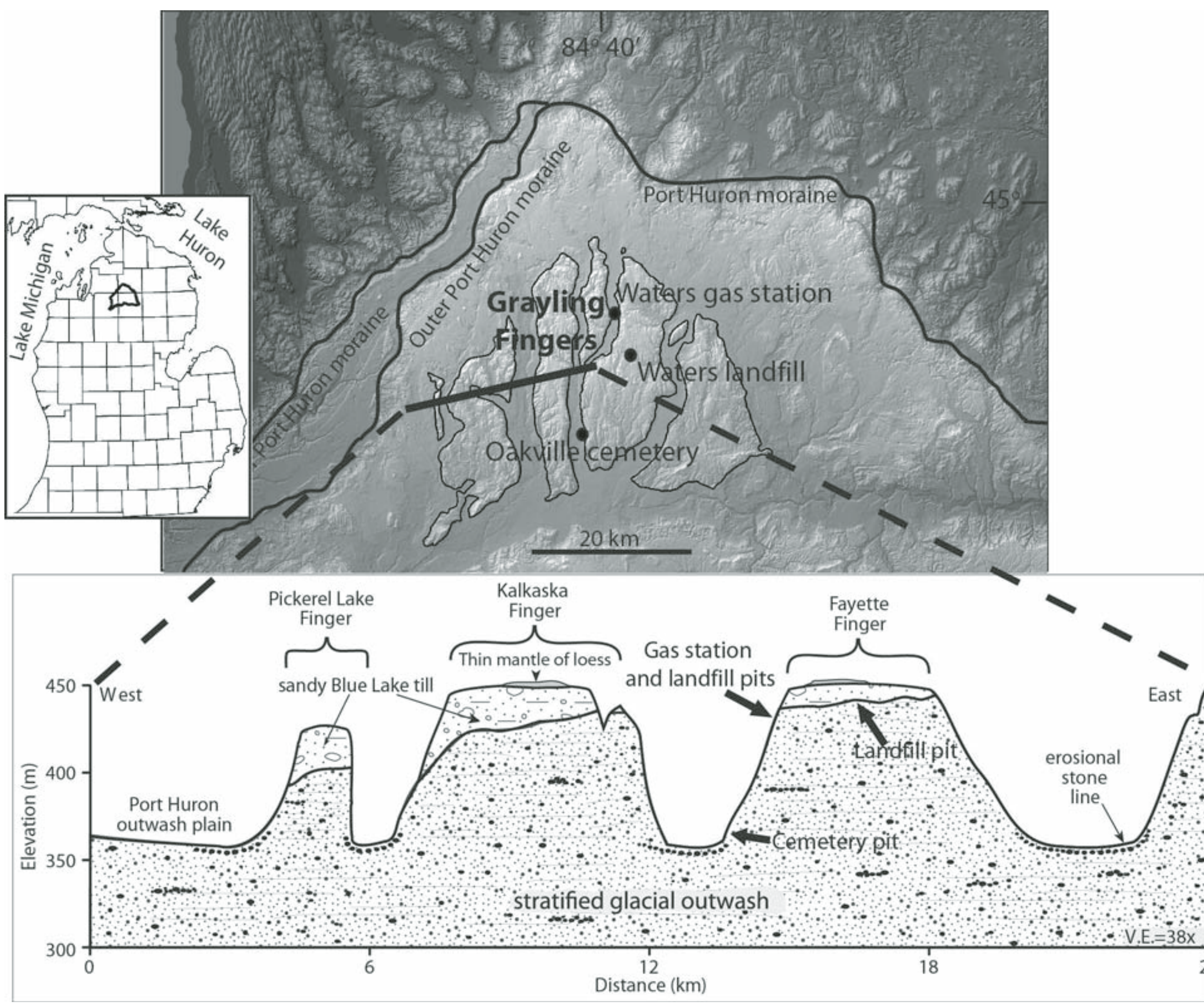

Figure 12. Map of the Grayling Fingers in the north-central part of southern Michigan illustrating the topography of the area, using a hillshade digital elevation model. The stratigraphic cross section is from Schaetzl and Forman (2008). V.E.—vertical exaggeration.

reentrant and referred to them as a "somewhat complex series of morainic ridges" (p. 230). Working on morphology alone, Leverett and Taylor (1915) concluded that, "the ridges from … the Au Sable River eastward appear to have been produced by ice moving westward from the Lake Huron basin, and those west … seem to have been formed by an eastward movement in the Lake Michigan lobe" (p. 231). They reported several feet of "boulder clay" on some of the ridges, underlain by sand that may be 200 ft (61 m) or more deep, and they described the finger valleys as sandy and low in fertility, and as having been incised by "lines of glacial drainage" (p. 232).

The "morainic" nature of the Grayling Fingers was perpetuated on subsequent glacial maps. Martin's (1955) map symbolized each ridge as a moraine. Burgis (1977) similarly described them as "morainic remnants," giving many of them informal names. Farrand (1982a) mapped the finger uplands as having formed in "ice-contact outwash sand and gravel." Informed by the earlier work of Schaetzl and Weisenborn (2004), the NRCS in 2006 described the upland parts of these features as a till plain, while mapping the outer, sloping, and gullied portions as an "ice-margin complex." The glacial origins of the Grayling Fingers were unclear at best, prompting the following work.

In a series of papers, Schaetzl (2008), Schaetzl and Forman (2008), and Schaetzl and Weisenborn (2004) examined the evolution of the Grayling Fingers, largely informed by published NRCS soil maps. These maps showed three main "families" of soils across the Grayling Fingers: (1) a silt-rich soil series (Feldhauser) that became sandier with depth, found only on the flattest, highest parts of the Grayling Fingers; (2) a sandy soil series (Blue Lake) with a clay-rich Bt horizon; and (3) a variety of sand-textured soils (Rubicon, Kalkaska, and others) on finger uplands, on finger side slopes, and in finger valleys (Fig. 13). These maps were used to guide fieldwork, which investigated the stratigraphic and textural nature of the sediments for each soil series and their parent materials. In this respect, the work was among the first to use NRCS data in a detailed, GIS-informed, glacial and geomorphic mapping exercise, representing a distinct shift in both data and methods for this type of science in Michigan.

Both soil distributions and textural data helped to unravel the geomorphic evolution of the Grayling Fingers. The silty Feldhauser soils, found on the highest, flattest sites on the finger tops were derived from loess, mixed with sandy sediment below. The loess likely was derived in part from the adjacent Outer Port Huron outwash plain to the west, which postdates the Fingers (Fig. 13; Schaetzl, 2008). When the distribution of the silty soils was viewed in conjunction with the deeply gullied side slopes of the fingers, it became clear to Schaetzl (2008) that the loess had been deposited onto impermeable frozen ground; loess was eroded from all but the flattest upland sites, because of the frozen substrate. Gullies on the sides of the fingers were cut at the same time, presumably due to runoff from the frozen uplands. Blue Lake soils were found to have formed in a few meters of sandy till, named the Blue Lake till by Schaetzl and Weisenborn (2004). This till has randomly scattered coarse fragments and lacks noticeable stratification, but it exhibits a strong pebble fabric, suggestive of basal till (Fig. 14). Rose diagram elongate poll

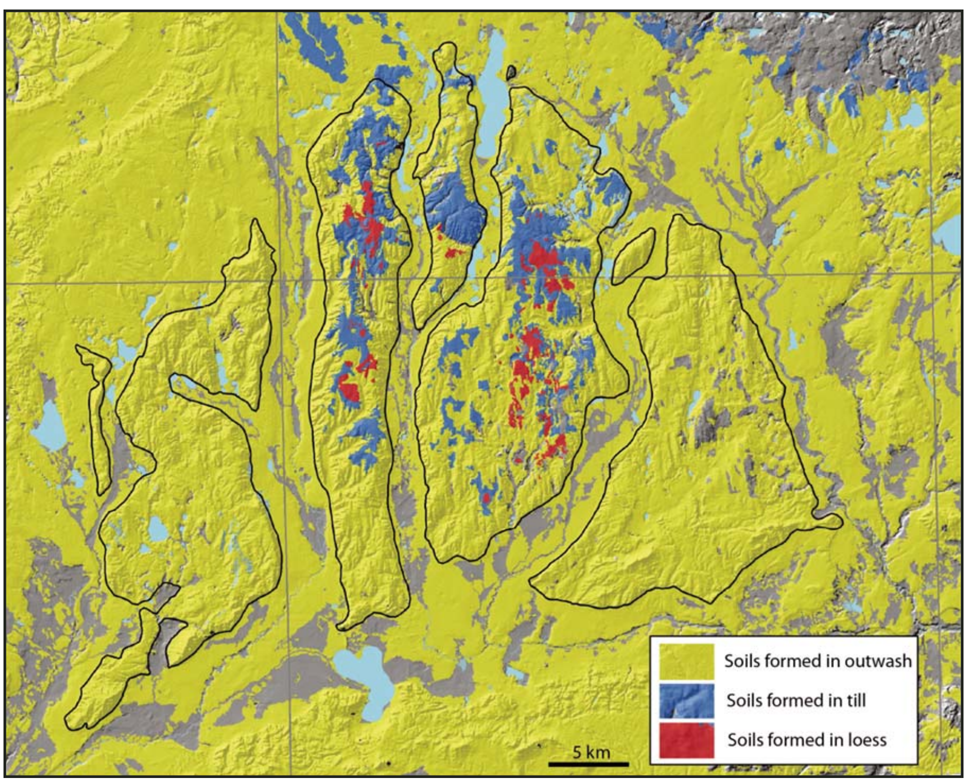

Figure 13. Soils in the Grayling Fingers region, grouped by parent materials.

orientations indicate that it was deposited by ice flowing southward, along the fingers, dispelling the notion implied by Leverett and Taylor (1915) that these uplands were formed by easterly or westerly flowing ice.

Last, the existence of extensive tracts of sandy soils developed in clean, well-sorted sand and gravel confirmed that the core of the fingers as well as the bottoms of the finger valleys were formed in glacial outwash (Figs. 12 and 13). Inspection of cross-bedding in this outwash indicated that it had been deposited in shallow, braided streams that flowed southward (Schaetzl and Weisenborn, 2004). OSL dates from three gravel pits suggested that the outwash was deposited between 29.0 and 25.7 ka, probably associated with a stable and stagnant marine isotope stage (MIS) 2 ice margin at the northern margin of the Grayling Fingers (Schaetzl and Forman, 2008). These dates establish that at ca. 29 ka, the MIS 2 (Wisconsin Episode) ice advanced southward over the Grayling Fingers and into the north-central part of the Lower (Southern) Peninsula of Michigan. To put this age in perspective, Lake Michigan Lobe ice first reached Illinois during the Michigan Subepisode at 29.45–27.93 cal yr B.P. (95% confidence range; Curry et al., this volume).

A topographic high on the underlying bedrock surface may have caused advancing MIS 2 ice to stall at the northern margins of the Grayling Fingers, forming a thick, broad outwash apron. If so, this part of southern Michigan may have remained ice free for a considerable period, even while areas much further south were covered with advancing ice. Ice eventually flowed south, across the region, depositing 5–10 m of sandy basal till over its own proglacial outwash plain. Upon retreat, meltwater formed the finger valleys. Much later, as ice readvanced to the Port Huron margin, meltwater aggraded the large Port Huron outwash plain, from which loess was generated, covering the fingers. Subsequently, loess was retained only on the flattest upland sites. Recent work shows that this area became subaerial much earlier than areas directly under the axes of the main ice lobes (Schaetzl et al., 2017).

Like some of the early pioneering work in Illinois that established the importance of knowing the relationships between soils and glacial sediments in land-use planning (Wascher et al., 1960; McComas et al., 1969; Berg et al., 1984), Schaetzl's work in the Grayling Fingers showed the utility of NRCS data in regional-scale glacial mapping in Michigan. In such an approach, the initial work involves establishing the genetic origin of soil parent materials, for example, Blue Lake soils and thin glacial till. Then, in a GIS, soil polygons are recoded to sediment types, resulting in a detailed surficial sediment map (Schaetzl et al., 2000). Interpretations beyond that point involve applying geomorphic and stratigraphic principles, thereby producing not only a map, but also an interpretation of the glacial history of the area. Of

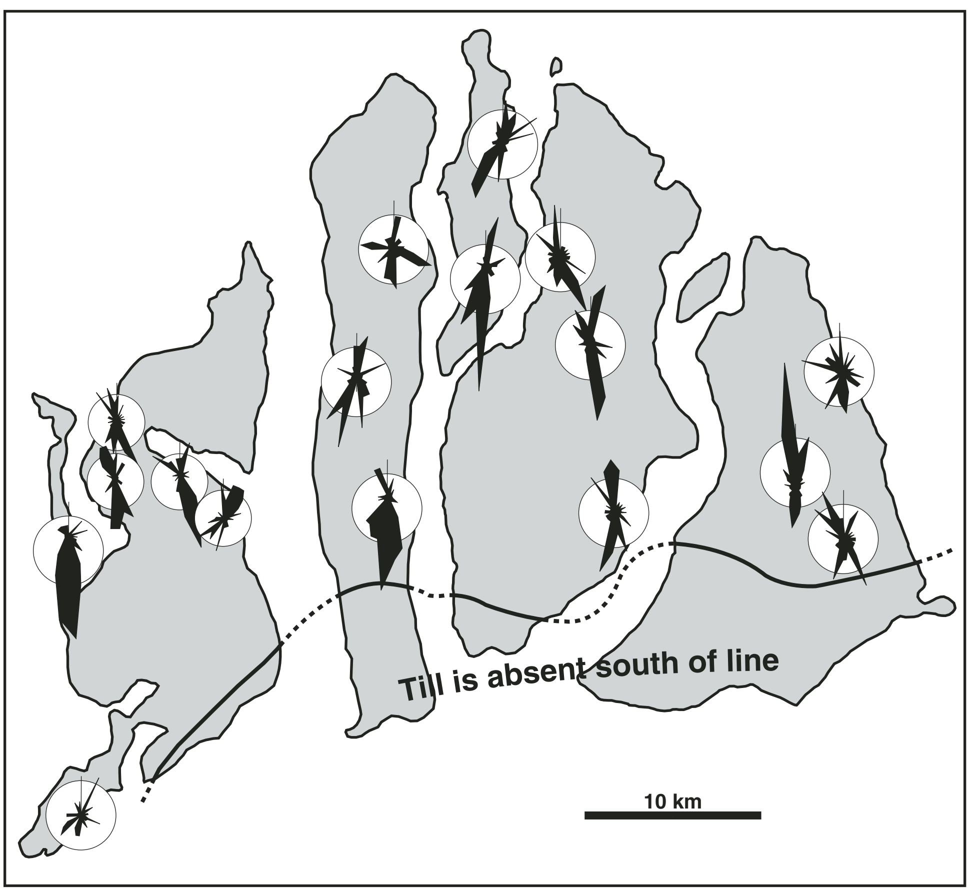

Figure 14. Rose diagrams showing the pebble macrofabric for the Blue Lake till, which is shaded and occurs on the summits of most of the Grayling Fingers. Rose diagrams are a standard method of showing the azimuthal orientations of elongated clasts, set within a broader matrix. Because these clasts are set within a matrix of (presumably) subglacial till, their orientations indicate the general direction of ice movement. After Schaetzl and Weisenborn (2004).

course, such maps are only as good as the NRCS maps on which they are based, and the user should apply and interpret such data with caution.

Inner and Outer Port Huron Moraines

Analysis of the Port Huron moraine west of the Grayling Fingers provides another useful case study for evaluating glacial mapping in Michigan. The moraine was first identified by Taylor (1897a) in southeastern Michigan and traced northward based on morphology (Taylor, 1899; Lane, 1899; Fig. 15A herein). Southwest of Gaylord, the moraine parallels the Lake Michigan coastline and splits into two distinct features, the Inner and Outer Port Huron moraines (named for their positions relative to the Lake Michigan glacial lobe). Each moraine is flanked by its respective outwash plains (Fig. 15B). Martin (1955), in the absence of any new work in this area, perpetuated the interpretations of Leverett and Taylor by mapping these features as moraines with flanking outwash. In his map legend, Farrand (1982a) delineated each feature as an "end moraine of coarse-textured till," flanked by "glacial outwash sand and gravel."

In cross section (Fig. 16), the Inner and Outer Port Huron moraines exhibit steep proximal slopes and gentle distal slopes, resembling a large outwash apron/fan. The crests of these features are, in places, hummocky and often exhibit an abundance of ice-contact and ice-wastage landforms. Soil maps and reconnaissance mapping indicate that these crests are sometimes finer textured than the flanking outwash plains, giving rise to the interpretation that the former may be composed principally of till. Lacking detailed sedimentological data, and working within the confines of glacial geology as it was understood in the early 1900s, it was reasonable for Leverett and Taylor to interpret the broad, hummocky crests, with their slightly finer-textured soils, as end moraines, and the flanking plains as outwash aprons (Fig. 15B). This interpretation was perpetuated by both Martin (1955) and Farrand (1982a).

Later, Blewett (1991) and Blewett and Winters (1995) mapped and studied the Inner and Outer Port Huron features in the northwestern part of the Lower (Southern) Peninsula of Michigan. Here, the two landforms were especially well developed and, in the case of the Inner Port Huron feature and its adjacent outwash plain, contained large gravel pits that provided excellent exposures of the underlying sediments.

Based on a detailed analysis of the morphology and sediments, Blewett concluded that the Inner and Outer Port Huron moraines were better interpreted as complex, ice-marginal landforms composed primarily of stratified sediment (Blewett, 1991; Blewett and Winters, 1995), which they referred to as "heads of outwash." On the basis of sedimentary data from gravel pits on the Inner Port Huron and its adjacent outwash plain, Blewett (1991) concluded that sediments of these ridges were not "coarse-textured glacial till," as mapped by others, but instead, were proximal facies of heads of outwash graded to their various outwash plains (p. 162–163).

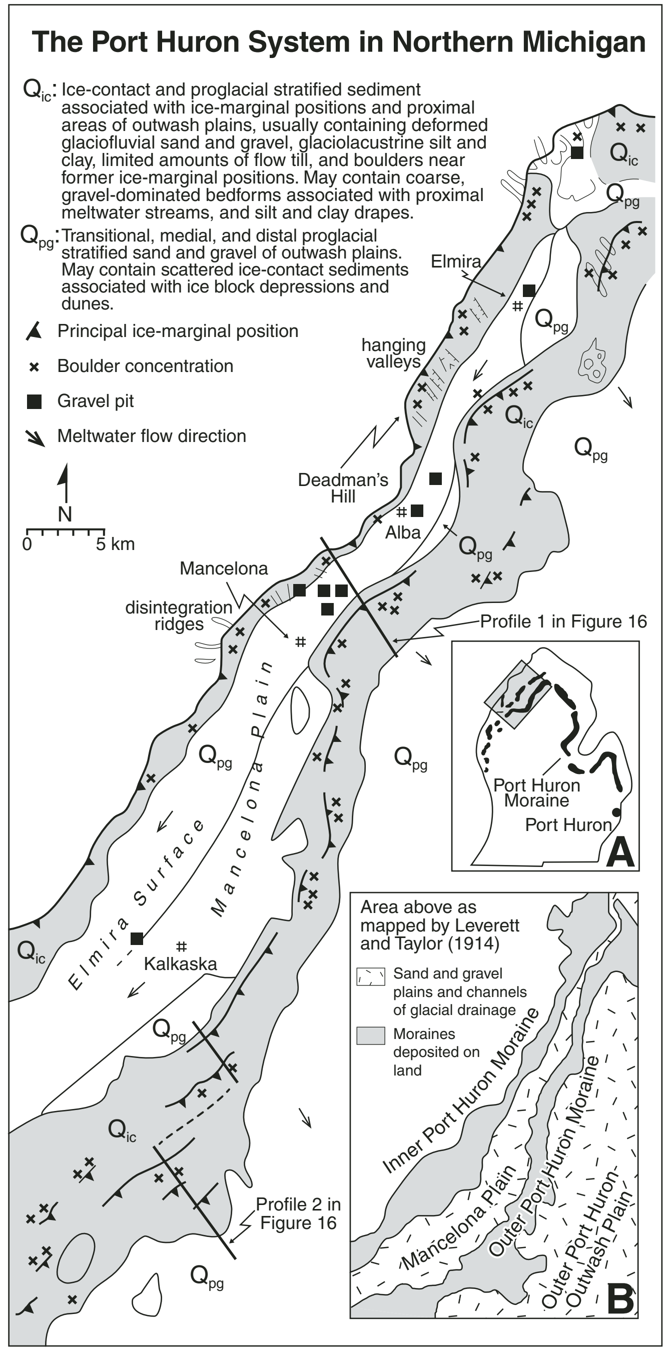

Figure 15. The Inner and Outer Port Huron system as mapped by Blewett (1991). Insets show the Port Huron moraine in (A) Michigan and (B) the Inner and Outer Port Huron moraines as mapped by Leverett and Taylor (1915). Smaller mapping units: Ql—lacustrine sand, silt, and clay; Qt—till, undifferentiated, not shown. Figure is after Blewett and Winters (1995), used with permission.

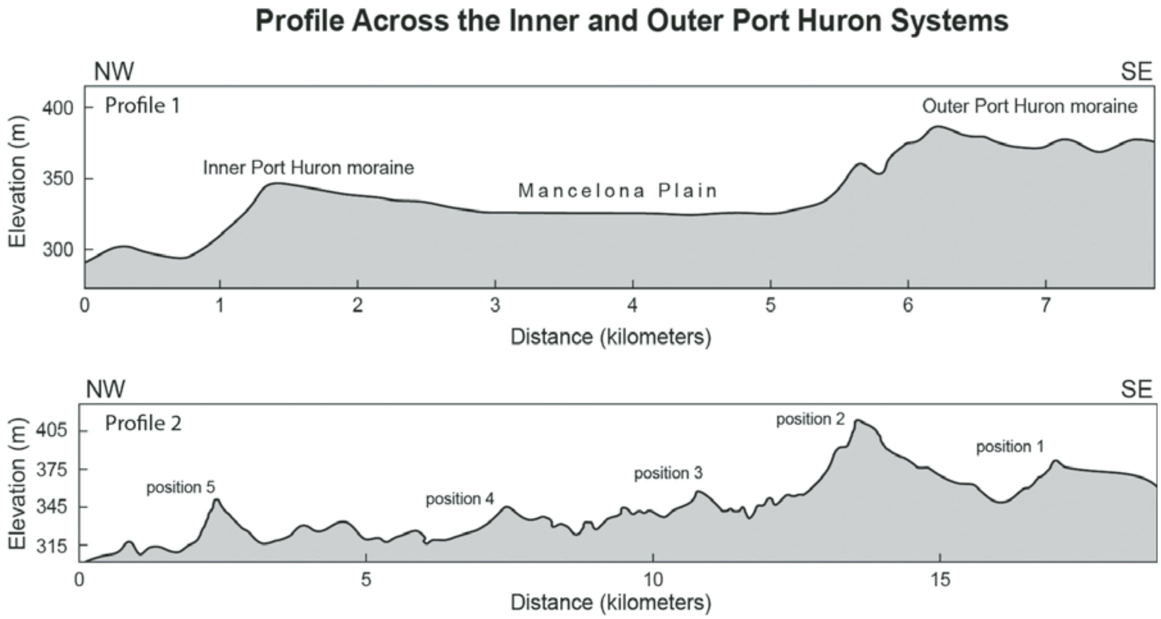

Figure 16. Profiles of ice-marginal positions associated with the Inner and Outer Port Huron systems (top), and a portion of the Outer Port Huron feature (bottom). Transect locations are shown on Figure 15. The bottom profile shows evidence for five ice-marginal positions within an area mapped by Leverett and Taylor (1915) as a single end moraine. These positions were verified by facies changes, boulder concentrations, and analysis of surficial sediments and bed-form lithofacies. Figure is from Blewett and Winters (1995), used with permission.

Although the genesis of heads of outwash is still debated (Gustavson and Boothroyd, 1987; Mooers, 1990), Koteff and Pessl (1981) reported on similar features in New England using a stagnation zone retreat model (Fig. 17), in which a narrow zone of stagnant ice forms along the glacier margin. Shear planes develop between the stagnant zone and the up-glacier mobile ice, transporting basal sediments to superglacial positions. Meltwater and gravity then transport these sediments beyond the ice margin, forming outwash plains, fans, and deltas. Proglacial sediments typically grade from coarse to fine with increasing distance from the ice margin, and boulders are common near the crest. These crestal areas typically display coarse-textured proximal outwash mixed with finer-textured sediments from clay drapes, flow tills, glaciolacustrine sediments, and the generally wider variations in meltwater flow regimes found in proximal outwash (Miall, 1983). Thus, the hummocky crestal areas are not typically developed on till deposited by direct glacial action, but they instead consist of poorly sorted outwash deposits and related sediments associated with the stagnant ice margin (Fig. 17). Upon the melting of the glacier, the area along the ice margin that served as the apron's head of outwash collapses to its angle of repose, forming a steep ice-contact slope. The result is an asymmetrical landform in profile that is highest and steepest on the up-ice side (Figs. 16 and 17), and dominated by glaciofluvial deposits (Fig. 18). As the active margin of the ice retreats, series of heads of outwash may be left in the landscape, recording subsequent ice-marginal positions.

The mechanisms for incorporating and transporting basal sediments to superglacial locations in the manner just described are limited (Weertman, 1961; Gustavson and Boothroyd, 1987; Mooers, 1990), and the formation of high-relief moraines containing thick accumulations of superglacial drift remain a topic of active research (Carlson et al., 2005; Larson et al., 2006). Until the details of these mechanisms are worked out, the stagnation-zone retreat model continues to provide a predictive construct for understanding glacial landforms and sediments in northern Michigan.

Blewett's surficial sediment map (Fig. 15) supplanted end moraines of coarse-textured till with ice-contact and proglacial stratified drift associated with heads of outwash. Ice-marginal positions were designated with lines rather than polygons, reflecting the distinctions between classical end moraines and heads of outwash. Price (1973, p. 19) recognized the importance of such distinctions and pointed out the error of "calling a ridge or a series of mounds of well sorted stratified sand and gravel a moraine, when there is abundant evidence that meltwater rather than ice is primarily responsible for its deposition." Although such statements may border on the dogmatic, they nevertheless emphasize the challenges of mapping complex glacial features using genetic terminology. Even so, informal usage of the term "end moraine" and "till" to describe these types of ice-marginal features will likely continue. These issues can be addressed easily, however, if Farrand's "ice-contact stratified drift" mapping unit can be incorporated and expanded in future mapping efforts. Clearly, these kinds of studies illustrate the complexity of the drift in Michigan, and the need for careful consideration of process-landform linkages when formulating mapping units.

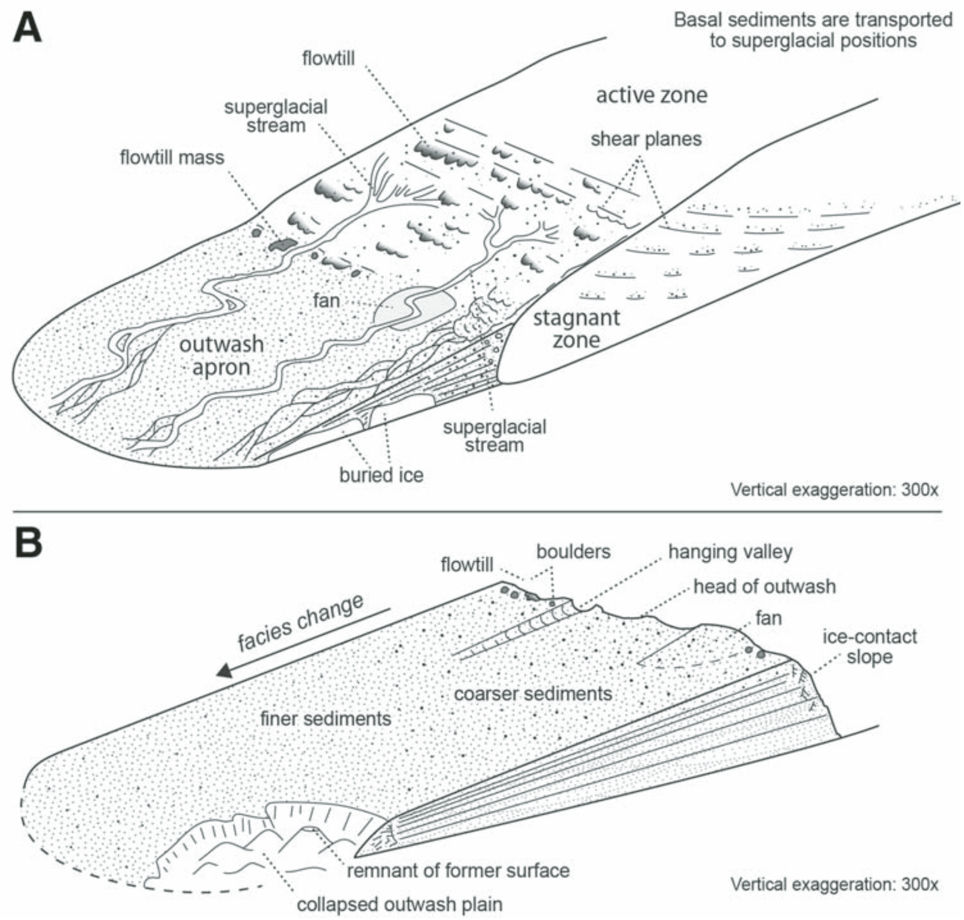

Figure 17. The stagnation-zone retreat concept as inferred from Koteff and Pessl (1981), showing one possible mechanism for the generation of heads of outwash. (A) The deposition of outwash and related sediments along a stagnant ice margin. (B) The feature after the ice has melted, causing collapse and formation of a steep ice-contact slope on the up-ice side of the outwash apron. The mechanisms proposed for incorporating and transferring basal sediment to superglacial locations are poorly understood (reviewed by Mooers, 1990). Figure is from Blewett (2012), used with permission.

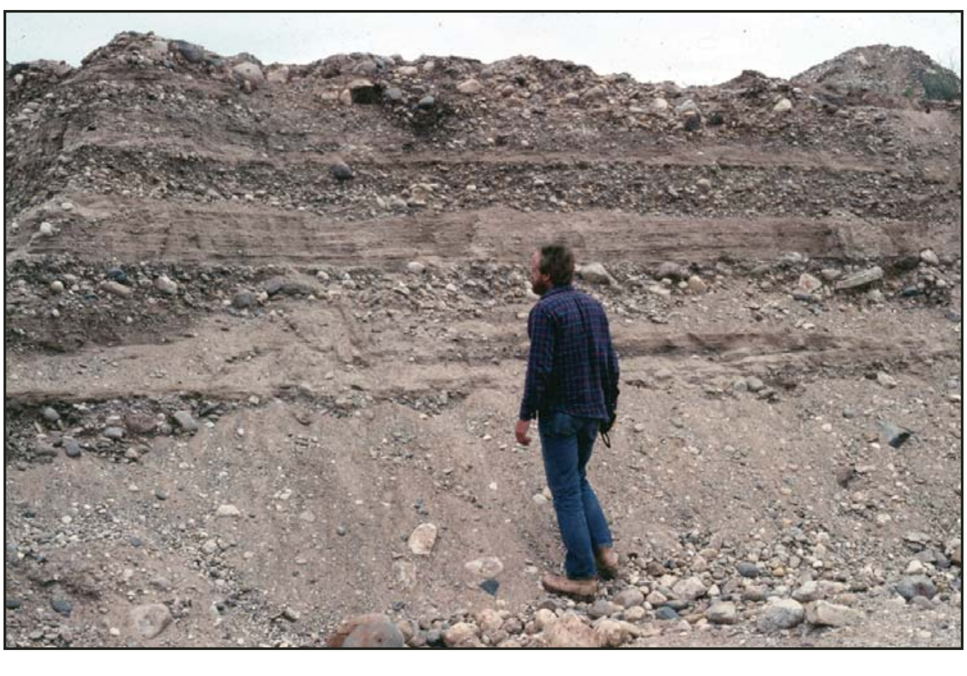

Figure 18. Longitudinal bar couplets associated with coarse, poorly sorted, proximal outwash, ~4 km north of Mancelona, Michigan. These sediments dominate extensive tracts of the Inner and Outer Port Huron crest, but they were mapped as "moraines deposited on land" by Leverett and Taylor (1915), "moraine" by Martin (1955), and "end moraines of coarse-textured till" by Farrand (1982a). Photo by R. Schaetzl.

Munising Moraine

Glacial mapping of Michigan's Upper (Northern) Peninsula has been particularly problematic, due to the paucity of exposures, the strong bedrock control in many areas, and the semi-wilderness character of much of the landscape, which has hindered access. The potential for meaningful mapping continues to improve, however, with the advent of digital soils data, GPR, GNSS, and related geospatial technologies. The convergence of such data and technologies is well illustrated by the history of work on the Munising moraine, the northernmost of the two east-west–trending topographic highlands in the central Upper (Northern) Peninsula of Michigan (Fig. 4).

In his map legend, Leverett (1929) mapped this feature as a "Moraine … deposited on land," and a "Moraine … deposited in water or later covered by waters of glacial lakes." These delineations were based on his belief that the moraine had been inundated by Glacial Lake Algonquin (Schaetzl et al., 2002). Later, Bergquist (1936) made minor refinements to Leverett's maps of the moraine and its flanking outwash plain. These changes were later incorporated into Martin's (1957) map. Futyma (1981) studied the broad coalescing outwash aprons along the southern flank of the moraine. These aprons headed at the crest of the Munising moraine and terminated downstream in what appeared to be cuspate deltas graded to Glacial Lake Algonquin. Farrand (1982b) mapped the Munising feature as an "end moraine" of coarse-textured till. Blewett and Rieck (1987) studied a small portion of the moraine between Munising and Grand Marais in Alger and Schoolcraft Counties. Although limited by the lack of exposures, they were able to use the feature's conspicuous morphology, along with the mapping of surficial sediments, boulders, and soil maps, to reevaluate its origin. Rather than an end moraine of coarse-textured till, they interpreted the feature as a series of heads of outwash and related ice-disintegration landforms, delineating at least three different ice-marginal positions.

Drexler et al. (1983) rejected the presence of a Munising ice-marginal feature altogether. They interpreted the landform to be the result of thin glacial sediment draped upon a bedrock high. In its place, they proposed a new moraine, the Grand Marais moraine, which was attributed to deposition by ice from the Marquette readvance, ca. 11,580 cal. yr B.P. (Lowell et al., 1999), and which included parts of the original Munising moraine. This readvance was inferred from buried wood at the Gribben Lake site west of Marquette, Michigan. Their proposal left unresolved the fact that parts of their new Grand Marais moraine appeared to be graded to the main Glacial Lake Algonquin level, a lake that had drained ~1000 yr before the Marquette advance.

By the early 2010s, geotechnology had advanced to the point that some of these discrepancies could begin to be addressed. Blewett et al. (2014) studied the central section of the moraine and its flanking deltas between Munising and Newberry in detail. Using survey-grade GNSS devices and the methods described by Drzyzga et al. (2012), they examined relict shoreline positions and extended the Glacial Lake Algonquin data set built by Schaetzl et al. (2002), Drzyzga (2007), and Drzyzga et al. (2012) westward to the Munising moraine. They also used GPR to reveal sedimentary structures in the apparent delta.

Blewett et al. (2014) confirmed the existence of a large Gilbert-type, ice-contact delta they named the Munising delta. The convex inflection at the delta front, where the flat delta surface meets the top of the foreset slope, has an elevation of 261.5 m. Because this part of the delta must have been submerged during formation, the stage of the associated lake must have been higher. The geostatistical isobase model developed by Drzyzga et al. (2012) predicts an elevation of 265 m for the main stage of Glacial Lake Algonquin at this site along the delta front. Also, a nearby beach ridge (265 m) at the Newberry Correctional Facility yielded an OSL date of 12.5 ± 1.1 ka, roughly in accordance with estimates for the draining of the main stage of Glacial Lake Algonquin. Based on this and other evidence, Blewett et al. (2014) concluded that the Munising delta was graded to the main stage of Glacial Lake Algonquin and that mapping of the Grand Marais moraine (Drexler et al., 1983) and Munising moraine (Farrand, 1982b) was in need of revision. They also recognized that the Munising moraine was a composite feature likely related to both the Two Rivers and Marquette glaciations, and that glacial events in the region were far more complicated than simple reconnaissance mapping might suggest.

CONCLUSIONS

Leverett and Taylor's brilliance, perseverance, and attention to detail have made USGS Monograph 53 "the great book for the glacial geology of the Great Lakes region" (Baclawski, 2013, p. 213). Likewise, their various glacial maps formed the basis for all subsequent statewide glacial mapping, including that of Martin (1955, 1957) and Farrand (1982a, 1982b). Less appreciated, perhaps, is the fact that these maps were based almost totally upon morphology, with the implicit aim of delineating the regional sequence of recessional ice-marginal positions and glacial lakes. Little attention has been given to processes as revealed by the sedimentology, or to the importance of stagnation and ice-contact deposits and landforms. Thus, for all practical purposes, the current maps of sediments and landforms in Michigan date to the early twentieth century, and, given the widespread significance of stagnation and glaciofluvial landforms, they are in critical need of revision.

Meanwhile, new technologies are revolutionizing traditional mapping methods. County-level digital soils data and 10 m DEMs coupled with GIS technology offer an especially promising avenue for improved glacial mapping. LiDAR provides exceptional promise for future mapping efforts, especially in forested areas. By 2022, these and other geotechnologies (e.g., sUAS) will have evolved further, new time-tracked horizontal and vertical reference systems (National Geodetic Survey, 2016) will be in place, and a framework will finally be available for measuring absolute tectonic movements and isostatic adjustments across the Great Lakes region.

The prospect of incorporating digital maps of local or subregional areas into an evolving statewide map of glacial sediment is at hand. The geospatial data Web site at the State of Michigan and the Michigan Geological Survey Web site likely would host such a map for free. With no publication costs, nor the need for capital investment in hard-copy inventory, we anticipate a bright future obtaining cost-effective, readily available maps of surficial deposits in Michigan. Such an effort would be in keeping with the notable collaborative efforts of the talented scientists of Leverett and Taylor's era.

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