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TOPOGRAPHIC AND SEDIMENTARY CHARACTERISTICS
OF THE UNION STREAMLINED PLAIN
AND SURROUNDING MORAINIC AREAS

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TOPOGRAPHIC AND SEDIMENTARY CHARACTERISTICS OF THE UNION STREAMLINED PLAIN AND SURROUNDING MORAINIC AREAS

By

Russell Leslie Dodson

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ABSTRACT

TOPOGRAPHIC AND SEDIMENTARY CHARACTERISTICS OF THE UNION STREAMLINED PLAIN AND SURROUNDING MORAINIC AREAS

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Streamlined hills within the Union Streamlined Plain form a continuum of related features which ranges from well-developed drumlins to rather indistinct swells. Associated photolinears are visible on aerial photographs. Two assemblages of streamlined landforms are present within the tract and are distinguishable based on differences in height, photolinear density, and the presence of non-streamlined accumulations of till.

Photolinear density, and elongation and height of the streamlined hills all exhibit notable spatial patterns. Statistical correlations between some variables can be interpreted to suggest that lower heights may be partly a function of increased erosion and that an increasingly coarse till matrix may lead to features with a more streamlined shape.

Differences in bedrock elevation and lithology have a marked influence on the matrix of the superjacent till. Leaching depths, and percentages of sand, silt, clay, calcite, dolomite, and total carbonates of the till can be divided into regions of higher and lower values. And for each parameter, much of the boundary separating the two regions not only is similar or identical to the others but also closely follows the trend of the drift-buried crest of the Marshall Cuesta. These characteristics are interpreted to represent a distinctive facies variation within a single till sheet, not the deposits of two glacial lobes.

The Tekonsha Moraine of the Saginaw Lobe has substantial contrasts in landform and drift characteristics between its eastern and western portions; there was much ice stagnation in the former, little to none in the latter. Additionally, placement of the distal margin for its easternmost part is markedly different from previous interpretations.

That portion of the Tekonsha Moraine of the Lake Michigan Lobe north of Scotts is technically not a moraine. Instead, most of it is a collapsed outwash plain marking an ice marginal position. Distinctive ridges indicative of ice stagnation are visible on aerial photographs of the feature.

Within the study area, the Huron-Erie Lobe advanced over terrain previously occupied by the Saginaw Lobe. And based on topographic characteristics, till fabrics, and 7/10A ratios of clay minerals, differentiation of the drift is possible at many locations. At some sites, however, lobal provenance is uncertain.

Streamlined hills which are genetically part of the Union Streamlined Plain are associated with all three Tekonsha margins and predate each of them. Finally, the Tekonsha Moraine of the Saginaw Lobe is correlative with its Lake Michigan Lobe counterpart, that of the Huron-Erie Lobe formed later.

To my dad and Dr. Brunnschweiler.

Both taught valuable lessons.

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The Department of Crop and Soil Sciences, Michigan State University and the Department of Geography, Western Illinois University provided laboratory facilities for the sedimentological analyses. The Geological Survey Division, Michigan Department of Natural Resources allowed convenient access to unpublished maps and manuscripts of Frank Leverett and Helen Martin.

I am particularly indebted to Elizabeth Bartels who typed the dissertation and Robin Schneider who did the cartography. Both of them made my job more tolerable. Furthermore, the editorial suggestions of Marjorie Winters substantially improved the final draft. Of course, I alone am responsible for any errors in this dissertation, be they typographical, conceptual, or otherwise.

Finally, "Doc" Goodman is ultimately responsible for this. Although he is blameless for any of my shortcomings, it was his enthusiasm which brought me into geography and changed my life.

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CHAPTER I

INTRODUCTION

Numerous parallel to near parallel, streamlined glacial landforms exist in those portions of Branch, Calhoun, Kalamazoo, and St. Joseph counties, Michigan that are bounded by morainic topography formed by the Saginaw, Lake Michigan and Huron-Erie lobes (Figures 1, 2). Their general alignment is north-northeast-south-southwest, thereby indicating formation by the Saginaw Lobe, and their topographic expression varies considerably, ranging from well-developed drumlins to much less distinct flutings. Additional lineations visible only on aerial photographs are also present. Both the streamlined landforms and surrounding morainic areas were formed during the Woodfordian (Late Wisconsinan).

Comparatively little detailed geomorphic research has been done on this portion of the state. Nonetheless, the increasing availability of large-scale topographic maps and aerial photographs has led to the recognition of a more expansive drumlinized region than was mapped by early investigators. Moreover, although the morphometry of the streamlined forms in a portion of the area has been described (Mills, 1980), for most of the tract there is no detailed documentation of their total extent, topographic characteristics, and associated sediments.

Drumlins or drumlinized topography have recently been identified in the adjacent morainic areas of both the Saginaw and Huron-Erie lobes (Shah, 1971; Johnson and Keller, 1972). The presence of these similar features within terrains of two different lobes raises questions concerning temporal and stratigraphic relationships and suggests a more complex deglaciation history than has generally been recognized.

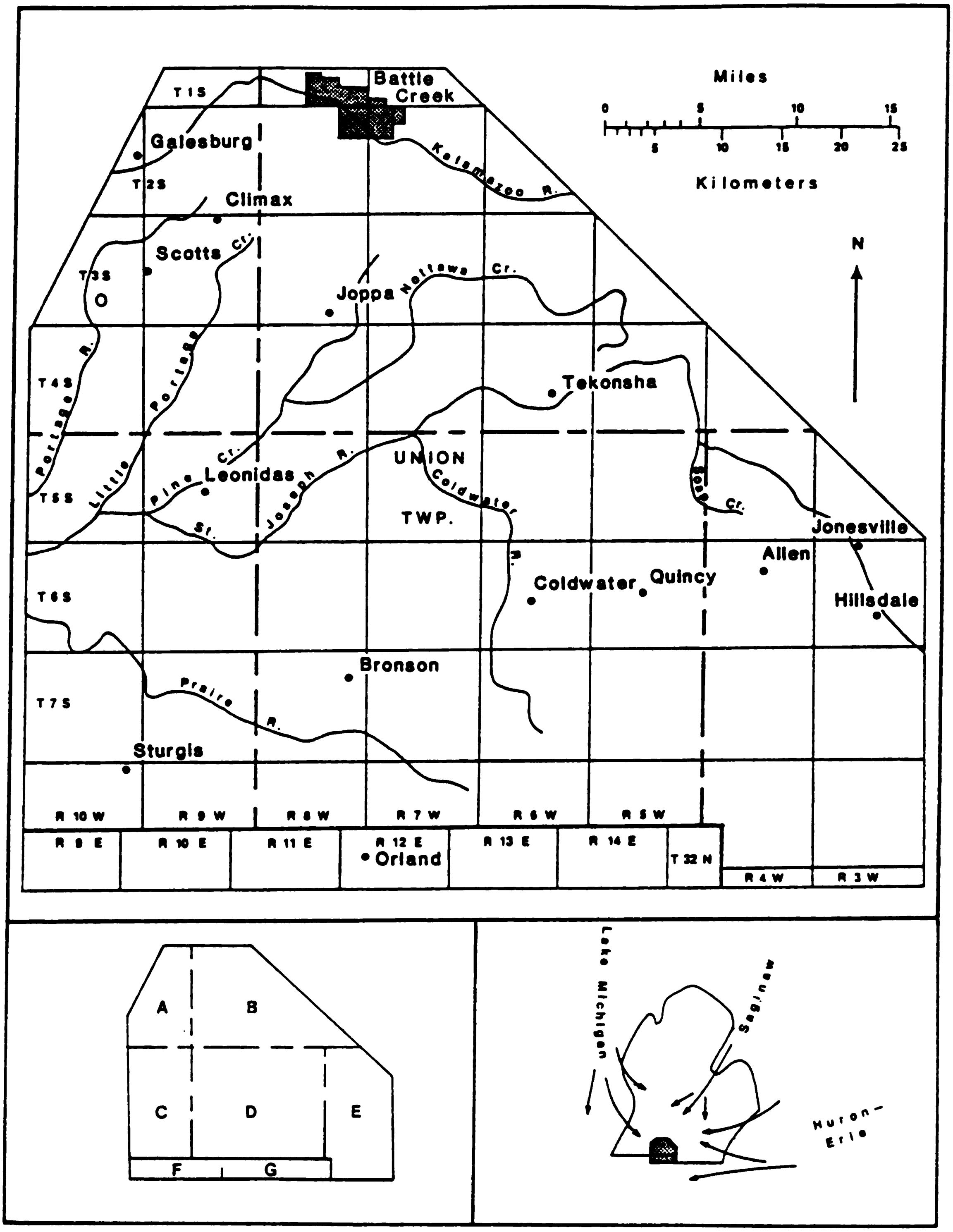

Figure 1. Map of the study area showing selected drainageways, towns, county and survey boundaries, and generalized lobate flow. Michigan counties: A, Kalamazoo; B, Calhoun; C, St. Joseph; D, Branch; E, Hillsdale. Indiana counties: F, Lagrange; G, Steuben.

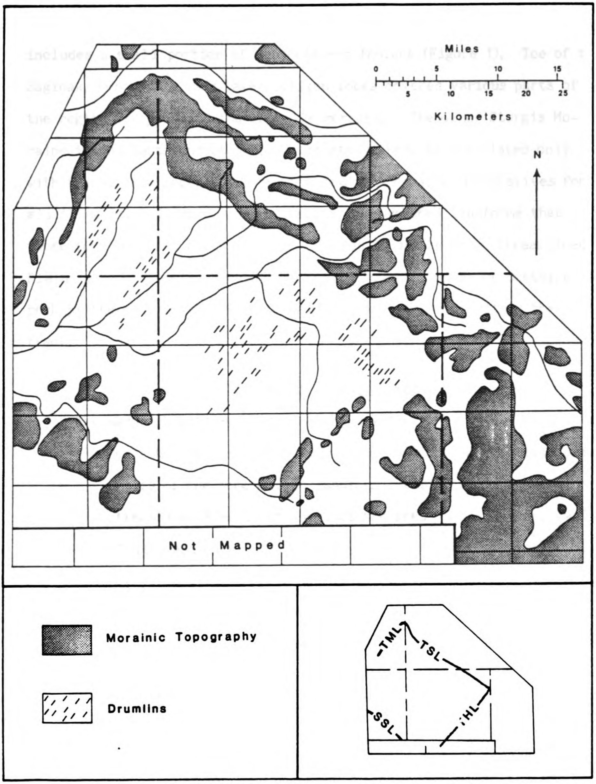

Figure 2. Drumlins, and morainic topography mapped as end moraines. SSL, Sturgis Moraine of the Saginaw Lobe; TSL, Tekonsha Moraine of the Saginaw Lobe; TML; Tekonsha Moraine of the Lake Michigan Lobe; THL, Tekonsha Moraine of the Huron-Erie Lobe (after Martin, 1955, and Farrand, 1982).

Study Area

The study area is located primarily in south-central Michigan but includes a small portion of northeastern Indiana (Figure 1). Ice of the Saginaw, Huron-Erie, and Lake Michigan lobes covered various parts of the region and produced four notable moraines. The older Sturgis Moraine is the southernmost and, in the study area, is associated only with the Saginaw Lobe, but there are Tekonsha Moraine correlatives for all three lobes (Figure 2). The area of streamlined landforms that these four moraines bound will be referred to as the Union Streamlined Plain, a name selected because the survey township of Union contains perhaps the most inclusive variety of streamlined forms within the tract.

Statement of Objectives

The major objectives of this study are to:

1) Describe the morphology and measure certain morphometric properties of the streamlined landforms located within the Union Streamlined Plain. Analysis of the areal distribution, variability, and interrelationships between these characteristics may yield insights into the origin and significance of the features. Further, these data will allow any future study to more fully compare and contrast these forms with those in other drumlinized areas.
2) Determine the spatial distribution and relationship to the bedrock surface of selected characteristics of the glacial sediments comprising the streamlined features.

3) Describe the adjacent morainic areas and investigate their relationship to the streamlined forms.

4) Interpret the deglaciation history of the study area.

Literature Review

Terminology of Streamlined Glacial Landforms

In a recent review article Menzies (1978/1979, p. 315) described drumlins as:

> Typically smooth, oval shaped hills or hillocks of glacial drift resembling in morphology an inverted spoon or egg half-buried along its long axis. Generally the steep, blunter end points in the up-ice direction and the gentler sloping, pointed end faces in the down-ice direction, these two ends being respectively known as the stoss and lee sides.

Drumlins with these characteristics, however, are only one of a group of related features including drumlinoid forms, flutings and groovings. All may be viewed as members of a continuum of streamlined, linear landforms produced by glacial action (Dean, 1953; Charlesworth, 1957; Flint, 1957, 1971; Aronow, 1959; Karrow, 1965; Prest, 1967; Sugden and John, 1976; and Aario, 1977).

Because of their transitional topographic characteristics, streamlined landforms have presented nomenclature problems and a number of authors use different names to describe similar or identical features (Dean, 1953). Others apply one designation to a variety of forms. For instance, Dodson and Winters (1977) followed the example of Gravenor and Meneley (1958, p. 715) and utilized the term fluting "in its widest possible sense..." to include low-lying drumlins, giant grooves, and parallel shallow grooves. Similarly, Menzies (1978/1979) considered features originally described as flutings (Dyson, 1952; Boulton, 1968) or drumlinoid forms (Dean, 1953) to be drumlins.

Drumlins and related streamlined landforms have been operationally defined in various ways. Among them are: 1) all forms in a drumlinized tract that exceed a specified height value, regardless of either the feature's shape or the presence of streamlining (Miller, 1972); 2) use of a height value in conjunction with some degree of elongation, such as two or more contours exhibiting an obvious longitudinal axis (Mills, 1980); 3) essentially circular forms as well as elongated ones (Hill, 1973); and 4) the exclusion of those forms without a definite elongation (Vernon, 1966). Clearly, there are considerable differences concerning the operational definitions of drumlins and related streamlined landforms.

Formation of Streamlined Features

Drumlins and related streamlined features are recognized in many different areas. Rather than being ubiquitous, however, they appear to have formed in large groups some distance proximal to a former ice margin. This restricted occurrence suggests that special conditions may be required for their formation and preservation (Muller, 1974).

Although studies are numerous, no single explanation of streamlined landform formation has been accepted (Menzies, 1978/1979). Various descriptions have emphasized erosion (Gravenor, 1953; Armstrong and Tipper, 1948; Aronow, 1959; Linton, 1963; Clayton and Moran, 1974; Whittecar and Mickelson, 1979), deposition (Flint, 1957, 1971; Smalley and Unwin, 1968; Sugden and John, 1976; Boulton, 1979; Menzies 1978/1979), or a combination of both (Kupsh, 1955; Charlesworth, 1957; Gravenor and Meneley, 1958; Evenson, 1971; Shaw and Freshauf, 1973) in their development.

Union Streamlined Plain

Areal Extent

Streamlined landforms in the Union Streamlined Plain were apparently first recognized by Leverett (1918a) and shown on his map several years later (Leverett, 1924a) (Figure 3). He placed the features in two separate till plains, one in southeastern Kalamazoo County and another just south of the St. Joseph River in Branch County. Bergquist (1941a, p. 452-3) also mapped drumlins in this area (Figure 3). And as did Leverett, he states that they exist on a plain, but, unlike any other worker, interprets it to be an "interlobate till plain ...formed by the combined activities of the Michigan and Saginaw lobes...." Furthermore, he depicts some of them on a small portion of what Leverett (Leverett and Taylor, 1915) initially, and Martin (1955) later, intepreted as the Tekonsha Moraine of the Saginaw Lobe. It should be noted, however, that Leverett's subsequent 1924 map portrays that particular area as distal to the moraine. Perhaps Bergquist interpreted the moraine in a manner similar to Leverett's later map. Alternatively, the location of the forms may be slightly misregistered. Martin (1955, 1957a, 1958) mapped drumlins farther south and east than any previous worker, showing most of them on till plains separated by sand-and-gravel-filled glacial channels and outwash plains (Figure 3). Johnson and Keller (1972) further expanded the tract's extent by mapping drumlinized topography immediately south and east of Coldwater, occurrences corroborated by Dodson (1974) and Dodson and Winters (1977), as

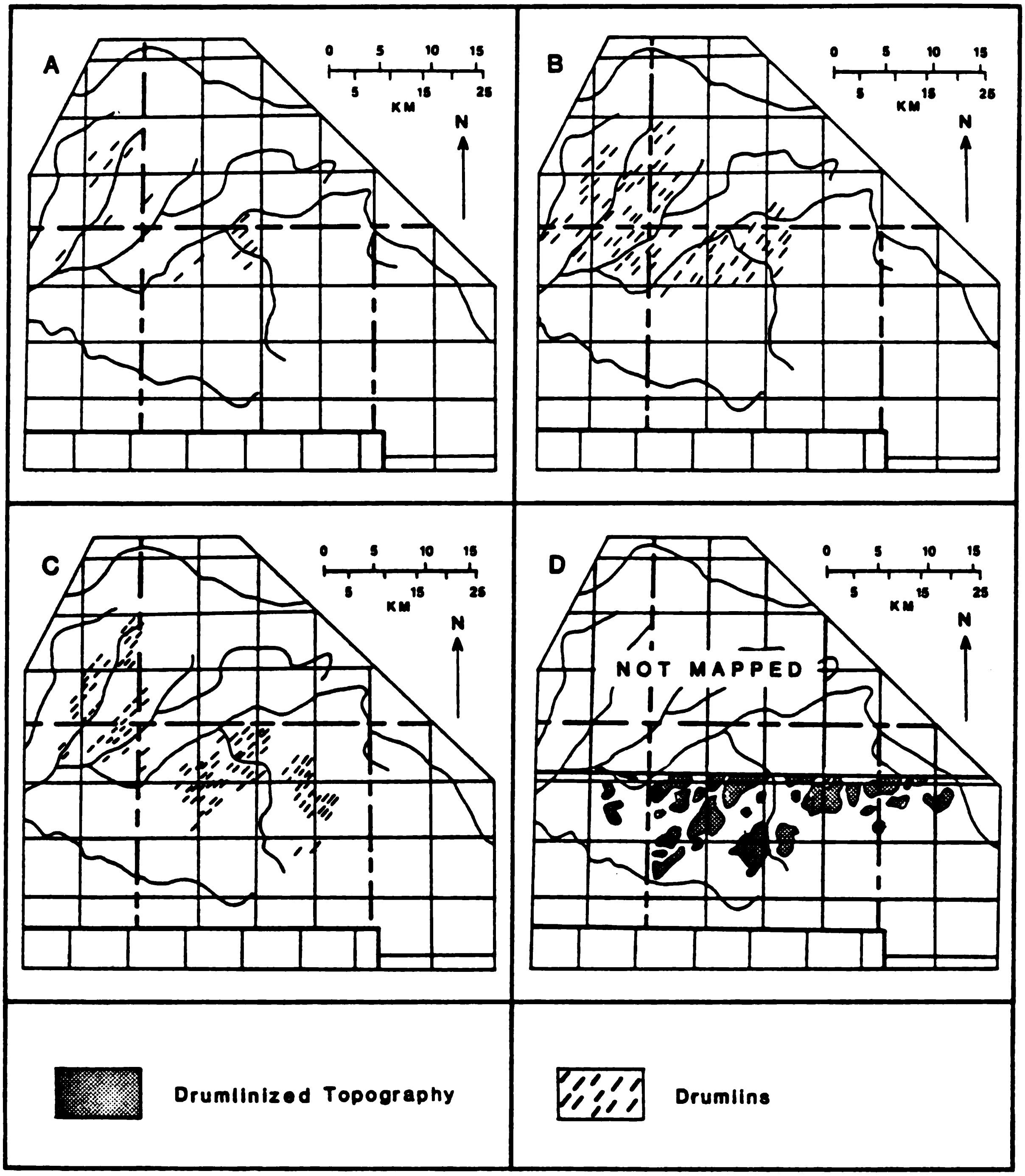

Figure 3. Differing interpretations for the extent of streamlined landforms in the study area. A, Leverett (1924a); B, Bergquist (1941a); C, Martin (1955); D, Johnson and Keller (1972).

well as on the discontinuous (inner) portion of the Sturgis Moraine. They also portray a narrow zone of streamlined features extending several kilometers east of Quincy. Virtually all of these latter forms, along with some south of Coldwater, are in areas mapped as moraines of the Huron-Erie Lobe by Leverett and Martin (Figures 2, 3). Moreover, both Martin, and Johnson and Keller portray drumlins or drumlinized topography proximal to their own placement of the Huron-Erie margin (Figure 3). Similarly, Shah (1971) reported drumlins associated with the Tekonsha Moraine of the Saginaw Lobe, but he neither described nor located the features.

Descriptions of the Streamlined Forms

Streamlined landforms in the area have been identified as drumlins, drumlinoidal hills or ridges, drumlinized topography, and flutings (Leverett, 1918a, 1924a; Bergquist, 1941a; Martin, 1955, 1957a, 1958; Zumberge, 1960; Johnson and Keller, 1972; Dodson, 1974; Dodson and Winters, 1977; and Mills, 1980). Bergquist described the forms he mapped as: roughly oval and more or less symmetrical in outline, with no appreciable difference between the stoss and lee slopes; trending from S 30 W to S 40 W; rarely over 11 meters (35 feet) high; and, ranging from about 200 to 1200 meters long and 160 to 320 meters wide.[1] Dodson, and Dodson and Winters report that the forms near Coldwater trend generally northeast-southwest, most ranging from 1 to 2 kilometers long and 200 to 600 meters wide, with crests 6 to 15 meters (20 to 50 feet)

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[1]All measurements will be given in SI units, irrespective of how they were originally recorded. However, to avoid cumbersome numbers, heights will be reported as an approximate metric equivalent followed by the English value in parentheses.

higher than adjacent lowlands. Mills (1980) measured morphometric parameters of the features within the northwest portion of the tract and gives their average values as: length, 575 meters; width, 274 meters; height, 8 meters (25.6 feet).

No report detailing the genesis of the streamlined landforms in the study area has been completed, although some general findings have been published. Bergquist (1941a) states that the features formed during an ice advance and Martin (1957a) writes that they apparently are erosional. Based on till-fabric data, Dodson and Winters (1977, p. 170) speculate that, prior to formation of the tract, Huron-Erie Lobe ice entered its eastern portion and deposited glacial till which was later streamlined by the Saginaw Lobe. They conclude that "if some of the drift did originate in this manner, then at least some of the flutes are erosional."

Sedimentological characteristics of the tract are poorly known; and, aside from the mapping of soils, no study to date has specifically investigated the glacial drift in detail. Till of the streamlined forms has, however, generally been described as clayey (Leverett, 1918a; Bergquist, 1941a; Martin, 1957a, 1958). Dodson (1974) and Dodson and Winters (1977) determined till fabrics for several streamlined forms near Coldwater and report that some of them are either poorly aligned or not oriented with the long axis of their associated features.

Bounding Morainic Areas

During final deglaciation of Michigan, the Saginaw Lobe margin retreated across the state line prior to those of either the Lake Michigan or Huron-Erie lobes. The first moraine it formed, and therefore the oldest in the state, was the Sturgis (Leverett and Taylor, 1915) (Figure 2). In subsequent mapping Leverett (1924a), Martin (1955), and Farrand (1982) reinterpreted the specific number, outline, and areal extent of morainic segments comprising the feature but retained its general location and trend (Figure 4).

Tekonsha Moraine correlatives exist for all three glacial lobes that influenced the study area (Figure 2). The Tekonsha Moraine of the Saginaw Lobe trends generally northwest-southeast along most of its course and forms the northern boundary of the Union Streamlined Plain. The Tekonsha Moraine of the Lake Michigan Lobe extends southwestward from the interlobate junction with its Saginaw Lobe counterpart (Leverett and Taylor, 1915). But substantial differences exist between earlier and more recent interpretations of its southern limit (Figure 4).

Leverett (Leverett and Taylor, 1915) depicted the Tekonsha Moraine of the Huron-Erie Lobe as a number of widely separated morainic tracts trending southwestward across central Branch County. Later mapping by him and other workers substantially altered the number, extent, and specific location of these elements but not their general alignment (Figure 4).

Deglaciation History

Relatively little detailed published work is available concerning the late glacial history of the study area and, in general, Leverett's (Leverett and Taylor, 1915) narrative remains the most comprehensive treatment. As described by him, following formation of the Sturgis Moraine and ice marginal retreat of the Saginaw Lobe, the three members

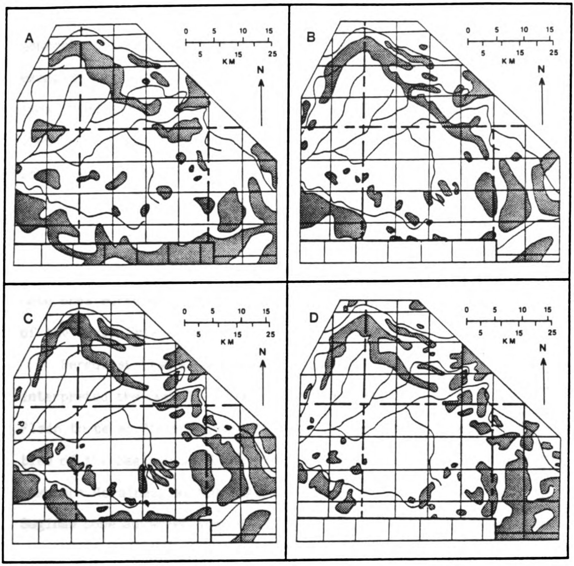

Figure 4. Differing interpretations for end moraines in the study area. A, Leverett and Taylor (1915); B, Leverett (1924a); C, Martin (1955); D, Farrand (1982).

of the Tekonsha Moraine were produced by ice of the Saginaw, Lake Michigan, and Huron-Erie lobes (Figure 2). But he continued to examine the general pattern of marginal withdrawal and lobal synchroneity. For example, in two unpublished accounts (Leverett, 1918b, 1924b) he specifically states what was only implied in the 1915 monograph, namely, that when the Sturgis Moraine was produced, the margin of the Lake Michigan Lobe was in western Kalamazoo County. Here it subsequently advanced over Saginaw Lobe deposits to form the Tekonsha Moraine. Furthermore, Leverett believed that the Saginaw Lobe experienced an appreciable readvance resulting in ice of the two lobes joining to form the interlobate area north of Climax. He also proposed a contemporaneous advance of the Huron-Erie Lobe.

Bergquist (1941a) envisioned a somewhat different sequence. He interpreted the terrain in the western portion of the Union Streamlined Plain to be an "interlobate till plain" produced by the combined activities of the Saginaw and Lake Michigan lobes. After formation of the Tekonsha Moraines, as the Lake Michigan Lobe held its position, the Saginaw Lobe advanced over the till plain, resculpturing its surface to form the drumlins. Shah (1971) postulated a similar drumlinizing advance. But Leverett (1918b) had previously stated that the streamlining happened about the time the Sturgis Moraine was forming, therefore without glacial overriding of the Tekonsha Moraine.

In two informal accounts, Martin (1957b, 1958) described deglaciation by the Huron-Erie Lobe as a progressive withdrawal from the Tekonsha margin interrupted only by a few quite minor readvances and some ice stagnation. She also depicts Saginaw and Huron-Erie lobe ice in contact in the area near Quincy.

Based on drainage relationships he associates with the Kankakee Torrent, Zumberge (1960) concluded that both the Huron-Erie and Lake Michigan lobes experienced appreciable readvances over terrain previously occupied by the Saginaw Lobe after the latter's ice margin had withdrawn to the position of the Tekonsha Moraine. Furthermore, withdrawal had initially proceeded still farther up-ice; only afterward did it readvance to form the feature. Finally, temporal relationships between moraines of the Saginaw and Huron-Erie lobes are unclear, but in places ice of the latter had overridden deposits of the former. Possible evidence for the opposite situation, Saginaw Lobe streamlining of Huron-Erie drift, has been presented by Dodson and Winters (1977).

In summary, several sometimes conflicting interpretations have been proposed. Major differences center on the following questions: 1) Was the Saginaw Lobe more extensive than present bounding moraines indicate? 2) Are the moraines of the Huron-Erie and Saginaw lobe correlative and, if so, in what fashion? 3) Did any or all of the lobes experience appreciable oscillations? 4) Was the Union Streamlined Plain produced before or after formation of the Tekonsha Moraine of the Saginaw Lobe? and 5) What is the relationship between the streamlined terrain and the moraines?

Procedures

Terminology for the Streamlined Features

The following general and somewhat arbitrary distinctions are applied in this study. The term drumlin is restricted to relatively well-developed, elongated, and streamlined hills, irrespective of the highest crest location or the presence of a steep stoss slope. Drumlinoid refers to less prominent but similar forms that have an easily delineated border. Flutings, although generally lower still, lack an easily recognizable outline. Photolinears are straight line segments, most of which appear only on large scale aerial photographs; some are clearly shallow grooves, but the relief on others is not apparent and they show up primarily because of tonal differences. The terms streamlined topography and drumlinized topography encompass all of the above forms.

Measurements

Morphometric data in this report are derived principally from topographic maps, although aerial photographs are used for additional information in ambiguous situations. Because the entire streamlined tract is mapped at a large scale (1:24,000) and photogrammetrically contoured with either a 5- or 10-foot interval, utilization of the maps facilitates quantitative assessment and results in objective, reasonably accurate, and reproducible measurements.

The morphometry investigation utilized the following procedures:

1) Only streamlined, elongated hills were studied. On maps with a 5-foot contour interval each had to be represented by two or more closed contours; only one was required on maps with a 10-foot interval.

2) The base of each feature was considered to be the lowest contour line according to the above criteria. In instances where adjacent landforms are connected by a low saddle or where a portion of the lower contour(s) diverge from the

generally elliptical outline, the technique of Mills (1980) was used. If the contour closure was at least three-quarters complete, and if stereoscopic viewing confirmed that the feature was streamlined, the contour was projected through the irregularity and treated accordingly (Figure 5).

3) Length and width were measured along the A and B axis, respectively, of the lowest contour.

4) Feature height was measured to the nearest 1.5 meters (5 feet) by calculating the difference between the top- and bottom-most contour. On maps with a 5-foot contour interval this procedure was straightforward but on those with a 10-foot interval it required interpolation. If the area enclosed by the highest contour was deemed large enough, the feature's height was recorded as 5 feet higher than that calculated. The elevation of the landform was considered to be the value of the lowest surrounding contour.

5) Except where spacing of the contour lines indicated otherwise, the central point within the uppermost contour was considered to be the highest place on the feature. The distance from there to the stoss and lee ends was used to calculate a ratio. The few forms with more than one closed contour along its crest, or those represented by only one contour, were considered to be indeterminate and assigned a value of 1.0.

6) K-values, a measure of streamlined-feature elongation, were calculated using the equation:

$$K = L^2/4A$$

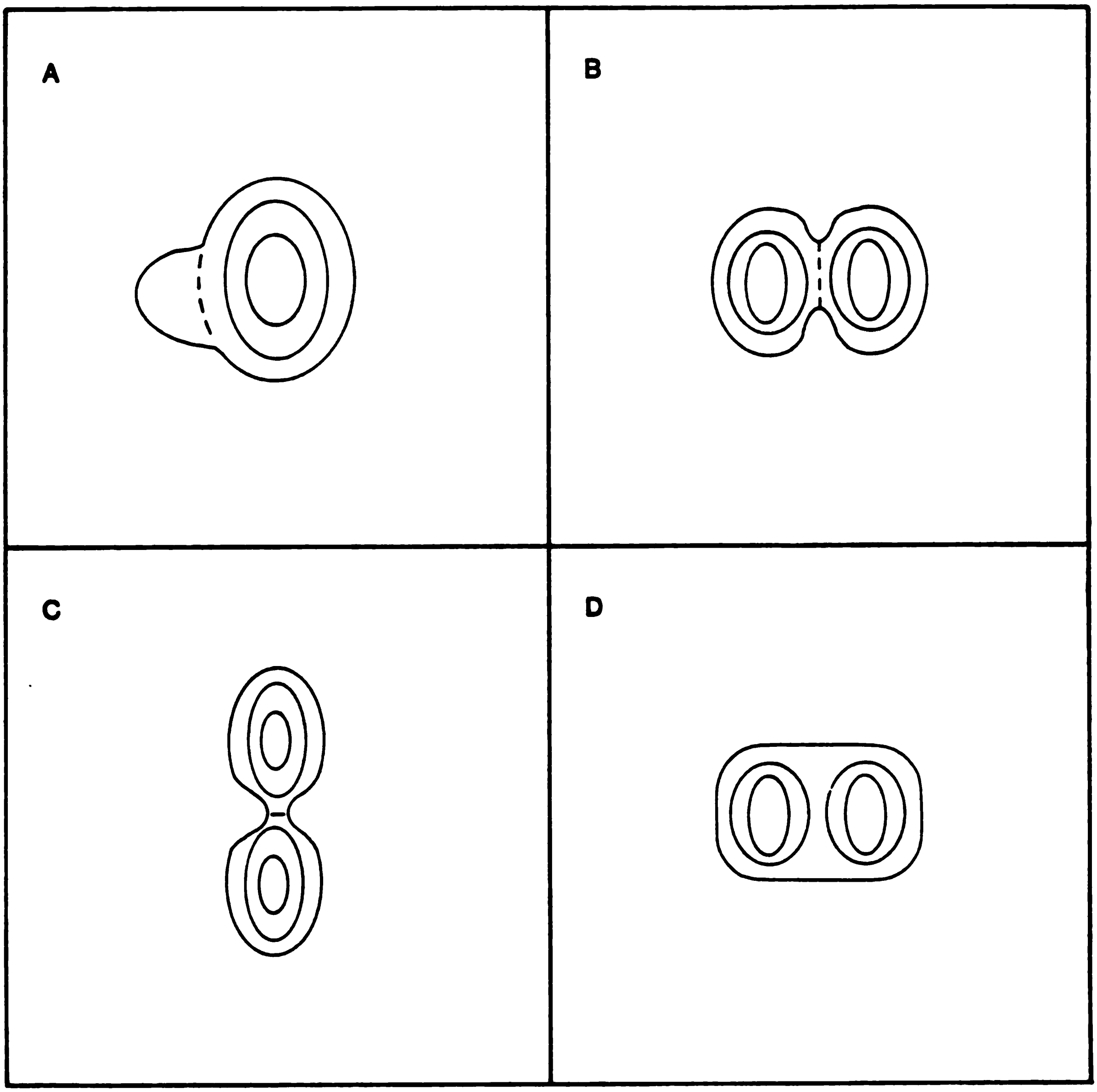

Figure 5. Projection of contour lines through A, an irregularity, or B and C, a low saddle connecting adjacent features. The outermost contour of D would not be projected between the hills (after Mills, 1980).

where L is the length of the form and A is its area (Chorley, 1959). A dot grid was utilized to determine the latter.

7) Photolinears were mapped from stereoscopically viewed aerial photographs with a scale of 1:20,000.

Topographic Representations

All of the topographic profiles in this dissertation were constructed by adapting procedures outlined by Koteff and Pessl (1981). Rather than a line transect, they portray a zone approximately 1200 meters wide. The resulting profiles tend to smooth out irregularities and depressions caused by the melting of buried ice blocks and yield a more representative cross section of the original depositional surface. It is an especially useful technique in areas of known or suspected ice-stagnation topography. Throughout this study, a zone 600 meters wide was found to be most convenient and that width was utilized.

Objectively drawn generalized contours also allowed inferences of the original depositional surface. They were constructed by taking the highest elevation in each 1/4 survey section, plotting that value at its center, and contouring the resulting data points.

Sedimentological Analyses

No systematic procedure was utilized to identify locations for collecting soil samples. Instead, accessibility and a subjective attempt to adequately characterize the area determined site selection.

Texture

All samples for textural analysis were collected below the level of carbonate leaching, that is, in the "C" horizon. Sand, silt, and clay percentages (USDA classification) were determined with a combination of wet sieving and hydrometer measurements utilizing procedures adapted from Day (1965).

Till Fabrics

The till-fabric methodology employed here is essentially that developed by Holmes (1941) and slightly modified by subsequent workers, such as Wright (1962). Every fabric determination was one meter or more beneath the surface, many in unleached till, and most, if not all, beneath the level of present frost action.

Only stones with an A:B axis ratio of 3:2 or greater and an A axis length ranging from 1 to 10 cm were included; those touching one another were omitted. The orientation and dip of each acceptable stone were measured to the nearest 5 degrees with a Brunton compass. For each site, azimuths were grouped into 15-degree intervals and, along with dip direction, portrayed on rose-type diagrams. Horizontal stones were plotted at half-value in opposite directions.

Clay Minerals

The 7A/10A ratio of clay minerals was used to characterize samples of oxidized, unleached till. Procedures modified from Jackson (1956) and detailed by Rieck (1976) were followed in preparing the samples. The process removes soluble salts, organic matter, and free iron oxides and yields a thin film of magnesium saturated, glycerol-solvated, oriented clay-sized particles (less than 2 micrometers) on a porous plate. The samples were exposed to nickel-filtered copper radiation in an X-ray diffractor. Peak heights for the 7A and 10A returns were measured and a ratio calculated.

Because none of the samples were potassium saturated or heat treated, the suite of clay minerals responsible for each peak is uncertain. However, in a study of Saginaw and Erie lobe tills in Jackson County, Michigan, Rieck (1976) reports that combinations of kaolinite, chlorite, and vermiculite appeared responsible for the 7A peak. Illite was the main contributor to the other peak.

Carbonate Content

Calcite, dolomite, and total carbonate percentages, as well as calcite/dolomite ratios of the less-than-200 mesh (.074 mm) fraction, were used to represent the original carbonate content of the till. This component was selected because, compared to other size ranges, it has a more constant composition, is a better reflection of relatively distant source rocks, and a small sample is sufficient (Dreimanis, 1960). Laboratory analysis utilized a Chittick apparatus and followed procedures detailed by Dreimanis (1962).

Not all of the carbonates dissolved in the solum are removed from the drift unit; some are precipitated at a lower level. In fact, dissolution and precipitation can happen many times (Salomons and Mook, 1976). As a consequence, drift in the zone immediately underlying the level to which leaching has progressed will contain more carbonates than it had when first emplaced, and samples collected from this horizon will yield values inappropriate for original carbonate content. In a study of loam, silt loam, and clay loam tills in Ohio, Wenner, Holowaychuck, and Schafer (1961, p. 316) examined this problem and concluded that, "to properly characterize parent materials of soils derived from calcareous Wisconsin till, samples must be taken at least 30 inches below the initial point of effervescence." Their procedures were followed in this study.

Depth of Leaching

Depth of leaching was determined with a 7 percent solution of hydrochloric acid. However, because dissolution and removal of the carbonate allows settling of the residue, the field measurements must, to some degree, under-represent the total thickness of drift from which they have been leached. Dreimanis (1957) apparently was the first to recognize this problem, and he recommends calculating a corrected depth of leaching using the formula:

$$h = 100d/n$$

where h is the original thickness of the leached zone, d is the measured depth of leaching, and n is the percentage of noncarbonates in the parent material. Within areas of low initial carbonate content neglecting this factor will probably not influence interpretations appreciably. But if the carbonate content is high (approximately 20 percent or more), or varies greatly from site to site, the differences between measured and corrected values for leaching depths could be substantial (Dreimanis, 1959).

Although carbonate-corrected values for leaching depths have not become a widely reported measure in glacial geomorphology, for the reasons given above both field measurements and total-carbonate-corrected leaching values are included in this study. The former is hereafter often referred to as LEA, the latter TCLE. When cited in the text, LEA depths are reported first, followed by TCLE values in parentheses. Procedures for locating sample sites on the streamlined hills are discussed in the Appendix.

Statistical Analyses

All satistical analyses performed for this dissertation utilized programs contained within the Statistical Package for the Social Sciences (SPSS) (Nie et al., 1975). Levels of significance of .05 or less were considered to denote statistical significance.

CHAPTER II

MORPHOLOGY AND MORPHOMETRY OF THE UNION STREAMLINED PLAIN

Introduction

Various morphological properties of drumlins and related streamlined landforms have enabled workers to postulate mechanisms responsible for their formation. For example, Alden (1918) and Fairchild (1929) interpreted concentric layering of fissility in the till comprising some drumlins to represent successive accumulations of material and an accretional origin. Conversely, truncated beds of stratified drift within certain drumlins in Wisconsin led Whittecar and Mickelson (1979) to propose that those streamlined forms were produced largely by erosion of pre-existing deposits.

Frequently, however, exposures are either lacking or not especially instructive. But, because properly selected morphometric parameters are related to process (Evans, 1972), analysis of such data can profitably be utilized and may corroborate or supplant morphological evidence. An excellent example of the latter is the demonstration by Chorley (1959) that k-value, a measure of drumlin elongation, is theoretically related to the velocity of the moulding ice or to the strength of the till.

Morphometric information has yet another merit in that it "provides an extremely useful basis for geomorphology, if only in suggesting the important spatial variables and structures that this science is to explain" (Evans, 1972, p. 18). Thus, these data can be used to formulate new and perhaps unexpected questions pertaining to landforms. This would seem particularly true if the same relationship was repeatedly observed from a number of geographical areas. Regarding drumlinization, therefore, the compiling of morphometric data from a variety of streamlined tracts is an essential activity even if its analysis does not immediately suggest or support any particular theory of formation. In this chapter both the morphology and morphometry of the streamlined landforms within the Union Streamlined Plain and the spatial patterns and statistical interrelationships for selected morphometric parameters of those features are examined.

Reinterpreted Extent of the Tract

The Union Streamlined Plain consists of that area of drumlinized topography distal to the three Tekonsha margins (Figures 2, 6).[1] As defined, the southern and southeastern margins of the tract are fairly coincident with the delineation of a map by Johnson and Keller (1972) that covers only a portion of the streamlined tract. The small differences reflect the transitional nature of the landscape rather than differing viewpoints. Leverett (1924a), Bergquist (1941a), and Martin (1955) did not recognize the streamlined landforms in this portion of the tract probably because of the indistinct nature of those features and the previous lack of large-scale topographic maps of the area.

Interrupting the generally rectangular outline of the streamlined plain is an approximately 13-kilometer-long, narrow extension first mapped, in part, by Johnson and Keller (1972). This area of Saginaw Lobe landforms is of fundamental importance because the region has traditionally been mapped as containing moraines of the Erie Lobe

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[1]Streamlined landforms also exist proximal to the Tekonsha margins but will be discussed in Chapter IV.

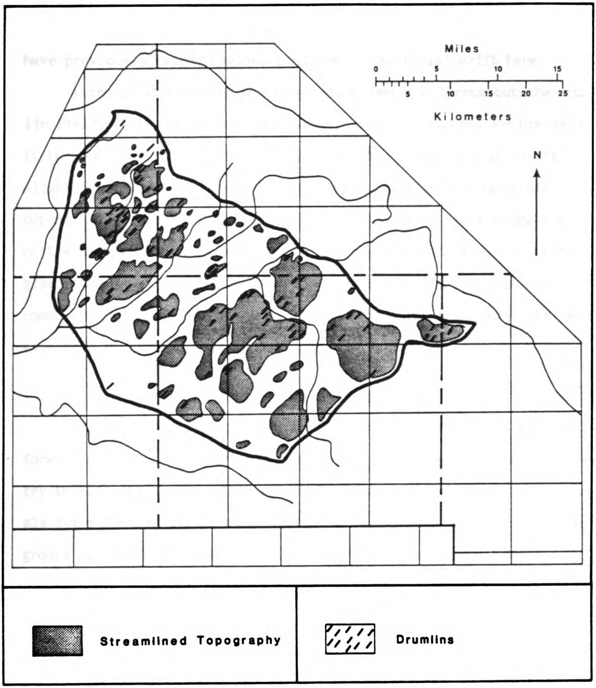

Figure 6. Drumlins and areas of streamlined topography within the Union Streamlined Plain.

(Leverett and Taylor, 1915; Leverett, 1924a; Martin, 1955; Flint et al., 1959; Farrand, 1982). To my knowledge, only Johnson and Keller (1972) have previously mapped Saginaw landforms or surficial drift here.

Although streamlined topography is widespread throughout the drumlin field, it is not present everywhere. Usually, but not exclusively, it is located on till plains of several square kilometers which are slightly higher than their bounding outwash plain and valley train deposits. Some of the streamlined forms, especially those along the northern margin of the tract, are buried to different levels by these glaciofluvial sediments. Because still more features are presumably completely covered, the original extent of drumlinization may have been even more widespread than mapped here.

Method of Analysis

The morphologic description of the streamlined forms is straightforward and needs no additional explanation here. But for the morphometry investigation, the method of identifying the samples and the rationale for selecting the parameters analyzed requires clarification. Two groups of linear features were selected for this analysis. The first consists of ten areas (termed sub-regions), each covering approximately 10 square kilometers, that are subjectively located in such a way as to reveal areal changes in landform expression (Figure 7). The sub-regions represent the type and variety of streamlined forms in their immediate vicinity. Their boundaries coincide with the till plains where feasible; elsewhere drainage divides were used. A total of 161 drumlins, drumlinoids, or flutings and 327 photolinears were identified within the ten areas. Average values for certain parameters (see

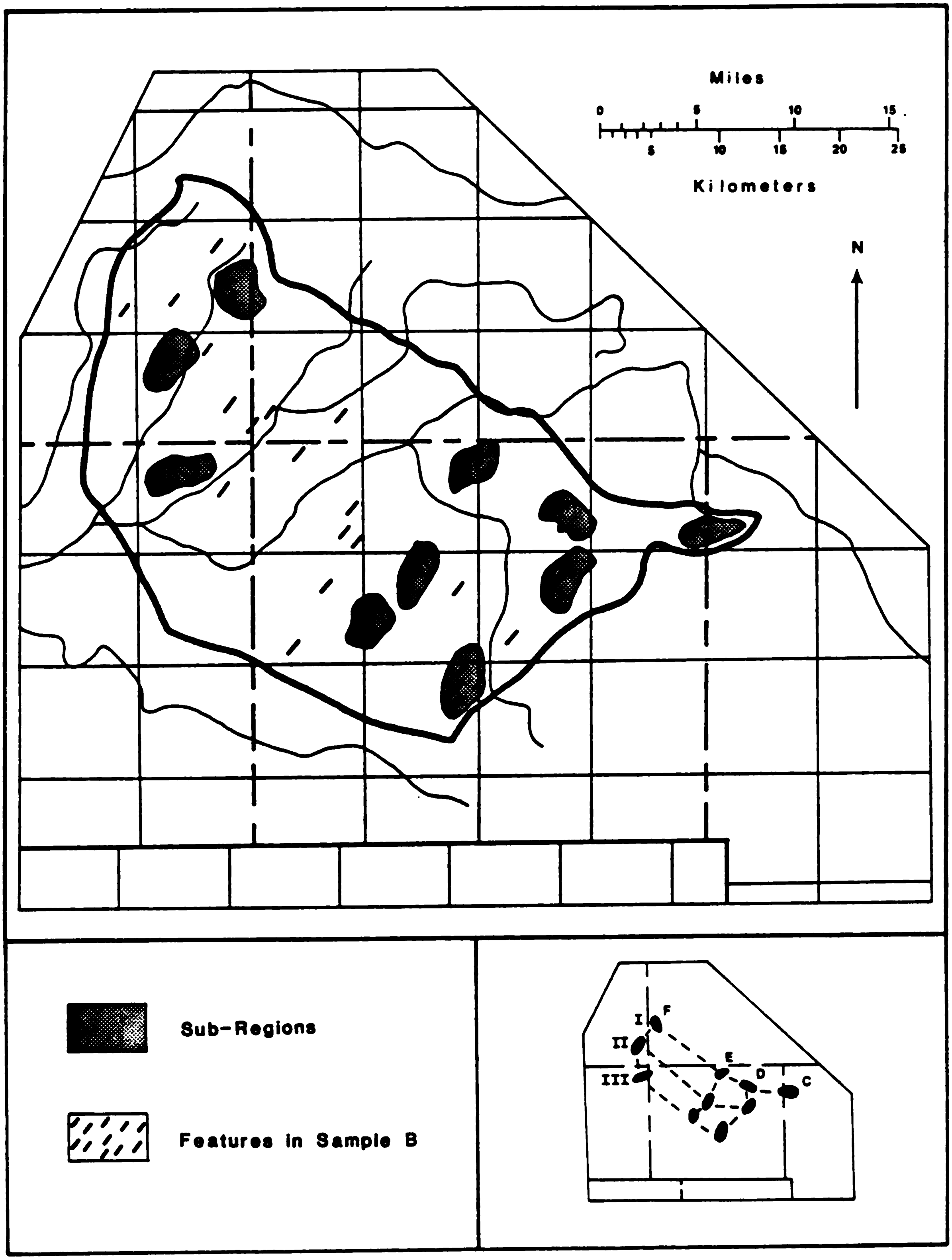

Figure 7. Location of the sub-regions, rows and columns, and individual features in sample B. See text for explanation.

below) were calculated for each of the sub-regions, thereby allowing examination of both spatial patterns and statistical interrelationships. Additionally, correlations based on the 161 individual features were determined and are hereafter referred to as sample A.

The second group analyzed, sample B, consisted of 29 streamlined hills located throughout the tract and selected in conjunction with a depth of leaching investigation (Figure 7). They were included in this study because information on till texture was available for each. Some of these features were in both groups though the two were identified independently. As with sample A, correlations for sample B are based on measurements of the individual features.

Length, width, length/width ratio, height, long-axis orientation, and asymmetry are the ratio scale variables most commonly used to describe streamlined forms (Mills, 1980). Each of these topographic parameters, as well as k-values, till texture, and photolinear length per unit area, were used. The measurement and interpretation of most of these are rather straightforward, but three--elongation, asymmetry, and till texture--require additional explanation.

Measures of feature elongation, length/width ratio and k-value, should not be confused with length; short forms may be quite elongated and long ones not. The former is more easily determined and probably more frequently cited (Crozier, 1975); but, unlike k-values, it lacks a demonstrated genetic relationship with streamlined forms (Chorley, 1959). Both measures were included in this investigation so that the data could be compared with the greatest number of other studies and to augment the discussion on genesis.

General statements or specific measurements on the presence or degree of long-axis asymmetry associated with drumlins and related streamlined landforms are frequently included in their descriptions. Various measures may be reported; for instance, percentage of forms with their high point nearer the stoss or lee end (Gravenor, 1974), field measurements of the stoss and lee slopes (Trenhaile, 1971), and stoss/lee ratios (Mills, 1980). Stoss/lee ratios have been calculated for all of the streamlined forms included in this investigation. Values less than 1.0 indicate features with their high points nearer the stoss end. The percentage of forms with high points nearer the stoss end has been reported as well.

Sand, silt, and clay percentages were determined for the parent material ("C" Horizon) of soils developed on each of the 29 landforms in sample B. Representative sedimentary textures for 9 of the 10 sub-regions were also determined for till samples collected from streamlined forms within or immediately adjacent to these areas. For the remaining sub-region, E-III, the predominant soil type mapped on the streamlined terrain therein was considered characteristic (Moon and Wildermuth, 1928). Sand, silt, and clay percentages for it were inferred from published soils data.

Results

Morphology

Landforms of the Union Streamlined Plain display a variety of sizes, shapes, and interrelationships. The positive topographic features form a continuum ranging from drumlins up to 14 meters (40 feet) high, through drumlinoids, to flutings, with the latter two being most numerous.

Many of the hills are smooth-crested ridges not joined to any other streamlined form. A large number, however, are arranged en echelon with one adjacent to and slightly offset from another. Compound forms consisting of more than one easily identifiable ridge exist, too, although they are generally restricted to the shorter, higher features in the western portion of the tract. The highest point along the crest is variable; on some it is nearest the stoss end and on others nearer the lee. A few display a slightly undulating crest giving rise to two or more "high points." Even less common are features where much of the mass is concentrated at either the proximal or distal end of a long, low, relatively narrow ridge. The visual impression of these latter features is one of a drumlin or drumlinoid form superimposed upon a low ridge. Few of the streamlined forms exhibit a steep stoss slope. Clearly, many of the features in the tract do not conform to "textbook" drumlin characteristics (Figure 8).

Photolinears are visible in varying concentrations on aerial photographs of the area (Figure 9). Many of these are not apparent in the field or on topographic maps. None of the linears are positive topographic features; instead, most appear to represent a slight "scraping" of the landscape. Some mark the change in slope along the base of the streamlined hills, thereby emphasizing the ridge, but many cross over or are located some distance from these features. A small number show clearly as shallow grooves. The majority are remarkably straight, parallel, or near-parallel to those nearby and range in length from a few hundred meters to several kilometers. Similar or identical

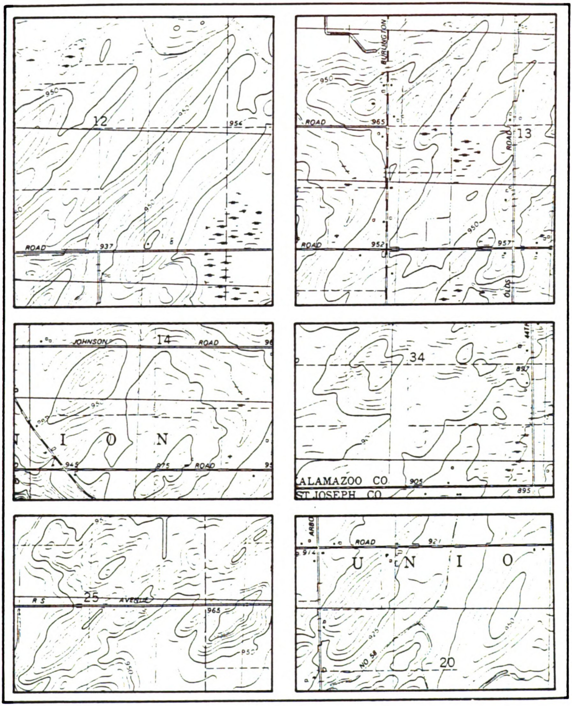

Figure 8. Examples of streamlined landforms within the Union Streamlined Plain as depicted on various 1:24,000 scale topographic maps. Contour interval, 5 feet.

Figure 9. Typical photolinears within the Union Streamlined Plain. Photo designation: BDE-2G-98, 7-1-50, scale 1:20,000.

features existing elsewhere have been described by Armstrong and Tipper (1948) and Dean (1953).

Regional Patterns

A slight splaying in the orientation of the streamlined forms and photolinears is present across the tract; for both, azimuths of 30 to 40 degrees are typical in the east, 40 to 50 degrees in the west. Elevations of the drumlins and related landforms decline from east to west reflecting the northwestward inclination of the regional slope. Values range from slightly above 320 meters (1050 feet) to just below 274 meters (900 feet), respectively.

Relief on the features also differs in the east-west direction. Subdued drumlinoids and flutings, many of which are not readily apparent in the field but are discernable on large-scale topographic maps and aerial photographs, predominate toward the east. But in the west the features are generally rather conspicuous. An exception to this pattern is the narrow, northeasternmost extension of the streamlined plain, where some of the features are as high or higher than those elsewhere in the tract. Throughout the area a general diminution in the height of the forms is noticeable in the down-ice direction.

Virtually the entire surface of the till plains in the eastern portion of the tract is smoothed and streamlined, a condition apparent on topographic maps, aerial photographs, and in the field (Figure 10). In the west, however, where a wide range of features exists, there is considerably more relief. Here prominent drumlins clearly separated from other forms, hills in which only their tops exhibit streamlining, and non-streamlined morainic masses are all present and intermingled

(Figure 11). And, because at some places adjacent streamlined and non-streamlined hills commonly have the same height, local relief does not seem to be the determining factor in their formation. The photolinears are most numerous in the central and southeastern portions of the tract. Regional patterns and differences for these and other landform characteristics are quantified in the section on morphometry.

Evidence for Glacial Erosion

Even though the photolinears appear to be erosional phenomena, their presence alone does not demonstrate that the associated landforms were formed by that process. It is conceivable that the lineations are a final but minor component in an aggradational sequence. Since they are still clearly visible, however, they do show that little or no glacial deposition occurred on them subsequent to their formation.

Till in the southeastern portion of the drumlin field tends to be more silty and clayey than that in the remainder of the tract. And it is here that shale bedrock is not only near the surface at many places but is often a conspicuous component of the till. These observations strongly suggest local erosion and incorporation of the bedrock into the till.[2] Again, this does not demonstrate that the associated streamlined forms are dominantly erosional, but it does imply that this process was a factor in their formation. A particularly revealing roadside exposure exists near the base of a flute located in SW Sec. 1, T. 7 S., R. 7 W. There a thin layer of colluvium overlies approximately one-half meter of till which in turn rests on highly weathered and totally disaggregated

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[2]See Chapter III for a more complete discussion of the sedimentological properties of the tract.

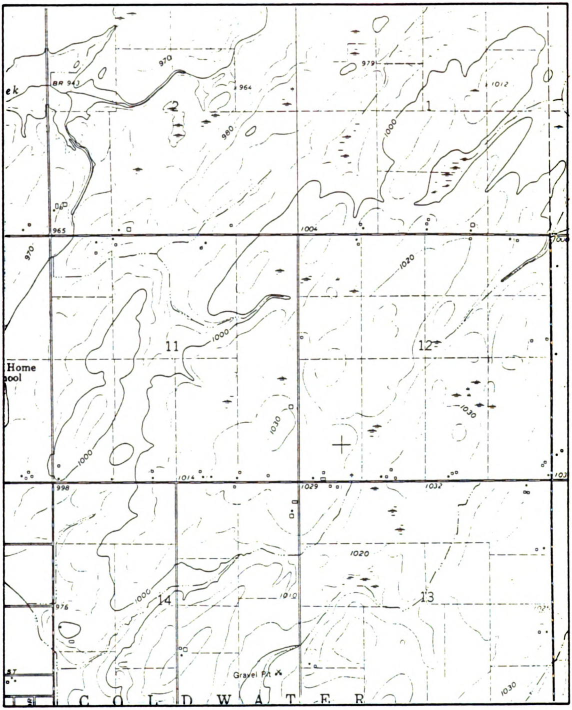

Figure 10. Typical topography within the eastern portion of the Union Streamlined Plain. Source: Coldwater East, 7.5' Quadrangle, 1:24,000. Contour interval, 10 feet.

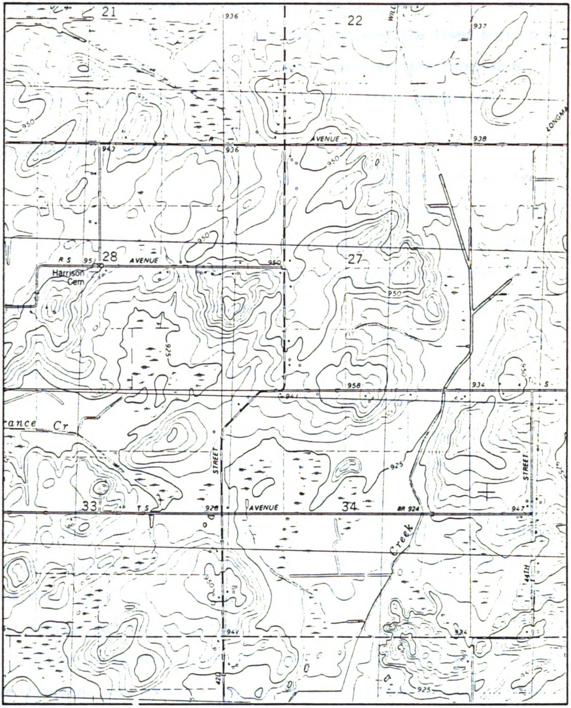

Figure 11. Typical topography within the western portion of the Union Streamlined Plain. Source: Climax, 7.5' Quadrangle, 1:24,000. Contour interval, 5 feet.

shale bedrock. The abrupt and planar nature of the lowermost contact combined with the observation that much of the till matrix is obviously derived from the local shale indicates that at least the lower portion of this fluting was eroded by glacial action. Moreover, the thinness of the till unit attests to the paucity of later glacial deposition.

Post-Streamlining Modification

The original relief on many of the streamlined landforms has been reduced by partial covering of sand and gravel. For example, just west of Coldwater several small, island-like streamlined masses are in the midst of valley train sediments. More striking topographic alterations are associated with outwash emanating from the Tekonsha Moraine of the Saginaw Lobe. Several kilometers southwest of the town of Tekonsha are features showing various degrees of burial. Adjacent to the moraine sand and gravel deposits are relatively thick and completely cover all older drift. As the elevation of this outwash surface lowers distally, however, the crests of progressively better expressed streamlined forms are revealed. Farther west, near Joppa, is an extensive area where glaciofluvial sediments form relatively flat-topped "uplands" surrounded by slightly lower, poorly drained land. In portions of these higher areas the tops of what appear to be "drowned" streamlined forms protrude a bit through the outwash surface.

Colluvium on many of the streamlined features indicates that they have undergone some modifications during or since deglaciation. Some, such as a drumlin in Sec. 11, T. 3 S., R. 9 W., have even been affected by both partial burial by sand and gravel and later colluvial activity. Since the maximum colluvial accumulation found within the tract was less than one meter, however, that process is not believed to have altered the landforms appreciably.

Morphometry

Table 1 summarizes the morphometric properties of selected streamlined features within the Union Streamlined Plain. Data presented are from this study and Mills (1980). The landforms in sample A are, on average, shorter, narrower, and less prominent than those in sample B. Means for length/width ratio, k-value, and stoss/lee ratio are, however, nearly identical. Averages from Mills' sample show the forms he selected to be shorter, wider, higher, less elongated and having a smaller stoss/lee ratio than those in either sample A or B.

The differences between these three compilations are partially a function of how the landforms were identified and selected. Sample A consisted of all streamlined forms within the sub-regions which were identifiable on topographic maps. It, therefore, contained a number of relatively subdued features. Sample B was not so all-inclusive. Mills only utilized forms at least 15 feet high which were randomly selected from a limited portion of the streamlined tract. Furthermore, his measurements were taken from a plane-table-contoured 15' topographic map with a 10 foot contour interval. All morphometric measurements in this study were obtained from photogrammetrically-contoured, 7.5' maps, many quite recent, with either a 5- or 10-foot contour interval. Therefore, both the variety of features examined and their measurements should accurately represent the streamlined landforms.

		Length (m)	Width (m)	Length/Width Ratio	K-Value	Height (ft.)	Stoss/Lee Ratio	Sand %	Silt %	Clay %
Sample A N=161	Minimum	134	38	1.4	1.2	5.0	.17	N/A	N/A	N/A
	Maximum	2196	488	9.6	9.6	40.0	3.60	N/A	N/A	N/A
	Mean	619	194	3.3	3.4	12.6	1.03	N/A	N/A	N/A
	Standard Deviation	344	88	1.4	1.4	8.0	.46	N/A	N/A	N/A
Sample B N=29	Minimum	317	122	1.7	1.7	5.0	.33	25	15	5
	Maximum	1464	519	6.4	6.1	40.0	2.20	80	58	26
	Mean	710	242	3.1	3.1	14.5	1.06	66	23	11
	Standard Deviation	309	104	1.0	1.1	8.4	.49	13	9	5
Mills (1980) N=25	Mean	575	274	2.2	N/A	25.6	.89	N/A	N/A	N/A
	Standard Deviation	175	94	.7	N/A	8.5	.27	N/A	N/A	N/A

Table 1. Ranges of values, means, and standard deviations for morphometric parameters associated with streamlined features in the Union Streamlined Plain.

Length

With the exception of sub-region E-II, average lengths of the streamlined features exhibit a striking across-ice pattern.[3] The progressive westward decline is shown in each of the three rows of Table 2.

Furthermore, all other sub-regions have average lengths greater than any of those in column F. No pattern was apparent in the along-ice direction. Simple correlations (r) between means for length and many of the other parameters are quite high. Those which were statistically significant are width, k-value, length/width ratio, stoss/lee ratio, and sand, silt, and clay percentages (Table 3).

Length is significantly correlated with width, k-value, and length/width ratio in sample A, but only with width and k-value in sample B (Tables 4 and 5). Thus, increasing length is associated with both wider and more elongated features, irrespective of whether the comparison is based on average values for the sub-regions or on either sample of individual forms. Chorley (1959) also noted that longer forms tend to be more elongated. The statistically significant relationship between average length and till texture in the sub-regions was not replicated by data from the individual features in sample B, thereby bringing its importance into question.

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[3]Although the Saginaw Lobe has long since melted away, directions within the study area will sometimes be referenced to it. Thus, "across-ice" and "along-ice" correspond to approximately east-west and north-south, respectively.

Columns

Rows	F		E		D		C	
	479	58	1004	37	629	50	684	60
	172	46	239	41	187	38	259	25
	3.1	44	4.3	42	3.6	38	3.1	33
I	3.2	4.1	4.2	7.9	3.4	4.8	2.8	1.6
	15.7	73	13.7	54	12.2	70	20.5	72
	1.12	19	1.52	29	1.16	20	1.03	18
		8		17		10		10
	509	71	689	40	705	33		
	182	47	198	38	192	38		
	3.2	45	3.5	40	3.3	39		
II	3.2	5.7	3.7	10.5	3.5	8.6		
	14.5	76	10.7	58	9.6	52		
	.77	16	1.34	27	1.40	32		
		8		15		16		
	449	66	538	83	709	100	a	g
	174	45	184	37	200	37	b	h
	2.8	43	3.0	39	4.1	38	c	i
III	2.7	4.5	2.9	9.0	3.9	7.4	d	j
	11.4	77	10.0	67	7.5	62	e	k
	.91	16	.87	23	.70	27	f	l
		7		10		11		m

Table 2. Average values for morphometric and sedimentologic parameters for each of the ten sub-regions; a=length (m), b=width (m), C=k-value, d=length/width ratio, e=height (ft.), f=stoss/lee ratio, g=stoss/lee percentage, h=azimuth of the topographically positive streamlined forms, i=azimuth of the photolinears, j=meters of photolinears per unit area, k=sand percentage, l=silt percentage, m=clay percentage. Locations of the sub-regions are shown in Figure 7. See text for a more complete description of each parameter.

	Length	Width	Height	K-value	Length/Width Ratio	Stoss/Lee Ratio	Sand	Silt	Clay	Photolinear Density
Length	1.000 (.001)	.719 (.010)	-.026 (.471)	.837 (.001)	.792 (.003)	.786 (.004)	-.783 (.004)	.712 (.010)	.853 (.001)	.334 (.173)
Width		1.000 (.001)	.521 (.061)	.490 (.126)	.234 (.258)	.477 (.082)	-.308 (.194)	.214 (.276)	.441 (.101)	-.208 (.282)
Height			1.000 (.001)	-.277 (.219)	-.377 (.141)	.132 (.359)	.446 (.098)	-.544 (.052)	-.262 (.232)	-.749 (.006)
K-value				1.000 (.001)	.938 (.001)	.555 (.048)	-.636 (.024)	.618 (.029)	.628 (.026)	.363 (.152)
Length/Width Ratio					1.000 (.001)	.614 (.029)	-.765 (.005)	.748 (.006)	.750 (.006)	.557 (.047)
Stoss/Lee Ratio						1.000 (.001)	-.659 (.019)	.566 (.044)	.770 (.005)	.242 (.251)
Sand							1.000 (.001)	-.987 (.001)	-.965 (.001)	-.729 (.008)
Silt								1.000 (.001)	.908 (.001)	.751 (.006)
Clay									1.000 (.001)	.653 (.020)
Photolinear Density										1.000 (.001)

Table 3. Simple correlation coefficients (r) for average values of parameters associated with the sub-regions. Levels of significance are in parentheses, N=10.

	Length	Width	Height	K-value	Length/Width Ratio	Stoss/Lee Ratio
Length	1.000 (.001)	.669 (.001)	.352 (.001)	.590 (.001)	.525 (.001)	.080 (.156)
Width		1.000 (.001)	.690 (.001)	-.060 (.223)	-.209 (.004)	.005 (.475)
Height			1.000 (.001)	-.134 (.045)	-.213 (.003)	.028 (.364)
K-value				1.000 (.001)	.913 (.001)	.147 (.031)
Length/Width Ratio					1.000 (.001)	.115 (.073)
Stoss/Lee Ratio						1.000 (.001)

Table 4. Simple correlation coefficients (r) for individual features in sample "A." Levels of significance are in parentheses, N=161.

	Length	Width	Height	K-value	Length/Width Ratio	Stoss/Lee Ratio	Sand	Silt	Clay
Length	1.000 (.001)	.801 (.001)	.163 (.199)	.396 (.017)	.303 (.055)	.242 (.103)	-.122 (.265)	.072 (.356)	.194 (.157)
Width		1.000 (.001)	.514 (.002)	-.176 (.181)	-.302 (.056)	.018 (.463)	.121 (.266)	-.129 (.252)	-.077 (.346)
Height			1.000 (.001)	-.426 (.011)	-.491 (.003)	-.152 (.215)	.340 (.035)	-.368 (.025)	-.209 (.138)
K-value				1.000 (.001)	.942 (.001)	.329 (.041)	-.502 (.003)	.442 (.008)	.510 (.002)
Length/Width Ratio					1.000 (.001)	.248 (.097)	-.351 (.031)	.284 (.068)	.405 (.015)
Stoss/Lee Ratio						1.000 (.001)	-.448 (.007)	.340 (.035)	.561 (.001)
Sand							1.000 (.001)	-.964 (.001)	-.848 (.001)
Silt								1.000 (.001)	.676 (.001)
Clay									1.000 (.001)

Table 5. Simple correlation coefficients (r) for individual features in Sample "B." Levels of significance are in parentheses, N=28.

Width

The westernmost sub-regions (column F) all exhibit narrower average widths than any other area, though there is no progressive east to west diminution. Average widths in columns F and D are remarkably consistent and have a range of only 10 and 13 meters, respectively. As with length, there is no pattern in the along-ice direction (Table 2). Aside from the above reported association with length, average widths do not have a statistically significant correlation with any other variable examined (Table 3).

In comparing individual features, only length (previously discussed) and height (discussed below) are significantly correlated with width in both samples. Length/width ratio attains significance only in sample A, although in sample B it is ambiguously close (Tables 4, 5).

Elongation

Dornkamp and King (1971), Trenhaile (1975), and Komar (1984) have reported that length/width ratios and k-values of streamlined forms are highly correlated with one another. Those findings are corroborated by data from this study; simple correlations (r) between these same parameters are greater than .9 and statistically significant in all three analyses (Tables 3, 4, and 5). But these two variables still exhibit differences in their relationship to the other parameters, some large enough to affect meaningful inferences. In sample B, for example, both length and stoss/lee ratio are significantly correlated with k-value; but neither are when compared to length/width ratio (Table 5).

The central zone of the tract (column E) tends to contain the most elongated features. With the exception of sub-region D-III, values in each row for both length/width ratio and k-value are greatest there. No pattern is apparent for either measure in the along-ice direction (Table 2). Aside from the earlier-reported correlation with average length, stoss/lee ratio is the only morphometric parameter examined that correlates significantly with either measure of elongation. Sand, silt, and clay percentages of the till were also significantly related to both elogation parameters; the finer the texture, the more elongated the forms (Table 3).

In samples A and B (Tables 4, 5), height and stoss/lee ratio are the only two morphometric variables (aside from length and width, previously discussed) significantly correlated with feature elongation; the former with both measures, the latter with k-value only. Perhaps more importantly, sand and clay percentages are also significantly correlated with both length/width ratio and k-value in sample B. This corroborates the till texture/feature-elongation relationship exhibited for average values associated with the sub-regions (Table 3).

Height

Average height decreases progressively down-ice in each column, and, with the exception of sub-region C-I which contains features as high or higher than elsewhere in the tract, from west to east in each row (Table 2). It is the only variable examined with both an along-ice and an across-ice progression. This pattern not only substantiates the earlier-stated generalization that the highest features tend to be located in the northern and western portions of the tract, but it emphasizes the height of the forms in the northeasternmost sub-region (C-I) thereby making their prominence even more notable. The only variable which manifests a statistically significant correlation with average height is photolinear density: the greater their concentration, the more subdued the forms (Table 2).

The correlation between height and width for samples A and B has been reported above but not discussed (Tables 4, 5). Although not a demonstration of causality, this relationship suggests that smaller widths inhibit the development of more prominent forms. It seems reasonable that a marked increase in height on too narrow a base requires inordinate amounts of either sub-glacial flow or shear for ice to traverse the developing landform. This situation could lead to either the termination of deposition or the initiation of erosion along the crest of the form.

Sand and silt percentages correlate significantly with height in sample B; positive for the former, negative for the latter (Table 5). Scattergrams of this data visually substantiate the close relationship and show that it is not unduly influenced by greatly anomalous sites (Figure 12). These observations appear to reflect a meaningful relationship and support the assertion of Karrow (1981) that drumlins are preferentially associated with sandy rather than clayey till. Several factors render such an interpretation suspect, however. For the subregions, till texture and average height lack both a statistically significant correlation and an areal correspondence (Tables 2, 3). Moreover, sand and silt percentages in sample B are more strongly correlated with k-value than with height, and height and k-value are themselves highly correlated (Table 5). This suggests that the correlations of sand and silt percentage with height may be a function of the relationship

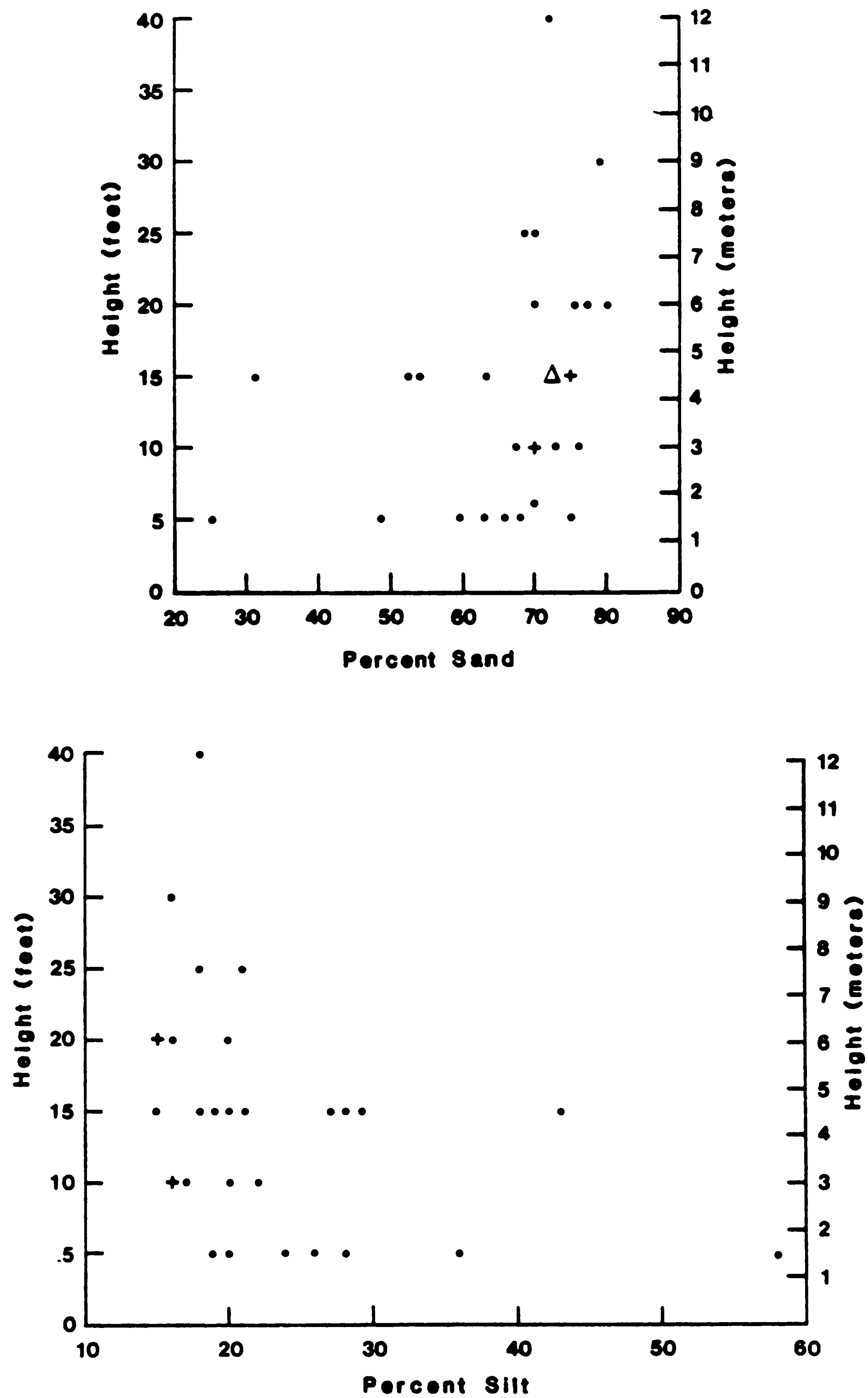

Figure 12. Scattergrams showing the relationship between feature height and percentages of sand and silt for sample B. Symbolization: • one feature, + two features, three features.

between elongation and texture. To assess this possibility, a partial correlation analysis was conducted.

Mathematically controlling for the effects of sand, silt, and clay, the correlations between height and k-value remain statistically significant or are only marginally rejected (Table 6). When k-value is controlled for, however, the correlations between texture and height weaken considerably and none approaches statistical significance. This suggests that till texture is not an important determiner of feature height. Therefore, the relationship between height and texture is, at best, ambiguous and possibly misleading.

Asymmetry

All of the northernmost sub-regions (row 1) have lower percentages of asymmetrical forms with their high points nearer the stoss end than do the southernmost areas (row 3) (Table 2). Stoss/lee ratios follow a similar pattern; all sub-regions in row 1 exhibit values greater than 1.0, all those in row 3 are less. Both measures, therefore, indicate a tendency for the features to have high points nearer their lee end in the proximal portion of the streamlined plain, nearer their stoss end in its distal part. This down-ice change is not progressive, however, nor is there a pattern for either measure in the across-ice direction. In none of the sub-regions does a majority of the streamlined forms have their high point nearer the stoss end, but for six of the ten that condition exists if indeterminate features are omitted.

Still comparing sub-regions, stoss/lee ratio is significantly correlated with length, k-value, length/width ratio, sand, silt, and clay (Table 3). The percentage of forms with high points nearer the stoss

Original values

	Length	Width	Stoss/Lee Ratio	Length/Width Ratio	Sand	Silt	Clay	K-value
Height	.163 (.199)	.514 (.002)	-.152 (.215)	-.491 (.003)	.340 (.035)	-.368 (.025)	-.209 (.138)	-.426 (.011)

Controlling for K-value

	Length	Width	Stoss/Lee Ratio	Length/Width Ratio	Sand	Silt	Clay
Height	.376 (.024)	.440 (.010)	-.036 (.428)	-.298 (.062)	.206 (.147)	-.274 (.079)	-.013 (.475)

Controlling for sand

	Length	Width	Stoss/Lee Ratio	Length/Width Ratio	K-value
Height	.219 (.131)	.506 (.003)	.001 (.499)	-.422 (.013)	-.313 (.052)

Controlling for silt

	Length	Width	Stoss/Lee Ratio	Length/Width Ratio	K-value
Height	.204 (.149)	.506 (.003)	-.031 (.438)	-.434 (.011)	-.315 (.051)

Controlling for clay

	Length	Width	Stoss/Lee Ratio	Length/Width Ratio	K-value
Height	.212 (.139)	.510 (.003)	-.043 (.414)	-.455 (.008)	-.379 (.023)

Table 6. Partial correlation coefficients between feature height and other selected parameters after controlling for k-value and measures of till texture. Levels of significance are in parentheses, N=29. See text for explanation.

end also evidence a relatively strong correlation with stoss/lee ratios (-.732) thereby demonstrating the compatibility of these two asymmetry measures (data not shown).

On over half of the asymmetrical forms in samples A and B, 61 and 53 percent, respectively, the high points are nearer the stoss end. Values drop to 30 and 31 percent if indeterminate features are included in the calculations. K-value was the only morphometric component significantly correlated with stoss/lee ratio in either sample (Tables 4, 5). And as with sub-regions, stoss/lee ratio in sample B is significantly related to measures of till texture: positively for sand, negatively for silt and clay (Table 5). Moreover, if only asymmetrical forms are included in the calculations, the correlations are raised substantially. Thus, relationships based both on individual features and on average values for sub-regions show that coarser till textures are associated with high points nearer the stoss end of the landform.

<u>Orientation</u>

Throughout the tract, average orientations of the streamlined hills and photolinears exhibit a close correspondence. In all sub-regions except C-I, the mean alignments are nearly identical and do not differ by more than two degrees. And even there the divergence is a relatively small eight degrees. Both parameters manifest a splaying pattern across the tract: slightly over 20 degrees for the streamlined hills, approximately 10 degrees for the photolinears. Each, however, displays quite consistent orientations in the along-ice direction (Table 2).

In comparing different drumlin fields, Mills (1980) reports a high negative correlation (r = -.850) between average length/width ratio and the standard deviation of drumlin orientation. He interprets this as supporting the hypothesis that feature elongation increases as ice-flow direction becomes more constant. Data from the Union Streamlined Plain do not substantiate this conjecture. But neither do they negate it. Both length/width ratio and k-value were moderately and negatively correlated with the degree of dispersion for orientation of streamlined features, but neither attained statistical significance. Values (r) were -.467 and -.537, respectively (data not shown). It should be noted, however, that the level of significance associated with k-values was .054 and could be viewed as ambiguous. Moreover, there are possibly confounding influences because this is an intratract comparison while Mills' analysis was between separate drumlin fields.

Density of Photolinears

Photolinear densities are greatest in the middle zones of the streamlined plain; all sub-regions in column E have values higher than those in their respective rows, and all in row II exceed those in their associated columns. Thus, in either the along-ice or across-ice direction, as one moves toward the margins of the tract, photolinear density decreases. Moreover, the four southeasternmost sub-regions exhibit values greatly in excess of all but E-I (Table 2).

Average height of the features and photolinear density show a notable association. With the exception of sub-region E-I, in those areas where the streamlined hills are most subdued (the four southeasternmost sub-regions) photolinears are most abundant. Along the northern and western margins of the tract (row I and column F, respectively) average heights are most pronounced and photolinear density less (Table 2). This areal correspondence is reflected by a quite high negative correlation (r = -.749). Significant correlations with sand, silt, and clay percentages also exist (Table 3).

Discussion

Within the Union Streamlined Plain two distinctive landform assemblages are present. In the southeastern portion of the tract virtually all of the landscape underlain by till is smoothed and streamlined, the forms are generally rather subdued and tend to merge into one another, and photolinear density is high. Because these characteristics, especially the concentration of photolinears, could easily have been altered by glacial action, it is clear that there was a general lack of post-streamlining glacial modification of any consequence. Perhaps more noteworthy, these observations, in conjunction with the site demonstrating glacial movement on bedrock and the presence of bedrock at or near the surface over much of the region, suggest an erosional origin for at least portions of many of the streamlined features there.

But the landscape in the western part of the tract exhibits many different characteristics: local relief is greater and the features more prominent; many of the streamlined forms are discrete entities clearly separable from those nearby; both streamlined and non-streamlined hills are present and in some places are adjacent to one another, but in other locations the latter seem superposed upon the former; and photolinear density is low. The presence of non-streamlined morainic masses, sometimes the same height as adjacent partially or fully developed forms, indicates that substantial penecontemporaneous or post-drumlinizing glacial deposition occurred. Otherwise, why would the ice preferentially sculpt only certain hills? This may in part explain the lower incidence of photolinears; many are simply obscured. But if there was also a relative lack of production, it would indicate substantially less erosion, at least during the final phase of streamlining. Perhaps more importantly, two characteristics of the streamlined hills--many are widely spaced and they rise noticeably above the level of the adjacent terrain--are criteria which Heikkinen and Tikkanen (1979) used to conclude that similar features in Finland were depositional in origin.

Irrespective of the above conjectures, the two landform assemblages are evidence of marked differences in the glacial regime between opposite sides of the Union Streamlined Plain. The virtual absence of deposits superimposed upon the fluted terrain in the southeastern portion indicates that the ice there contained little englacial material. Instead, most was below the glacier base and transport may have been accomplished by continuous deformation of the drift sheet in the manner proposed by Boulton (1979). Conversely, the widespread partially and non-streamlined accumulations in the west may indicate that the ice there carried substantially more englacial material and that much of it was deposited penecontemporaneous with or subsequent to streamlining.

Karrow (1981) has challenged the assertion or implication of some authors (e.g., Flint, 1947, 1971; Bloom, 1978) that drumlinized terrain is found mainly in areas of clayey till. He cites numerous areas where drumlins are composed of sandy till and demonstrates that the drift in some streamlined tracts, although originally described as clayey, is in fact sandy. He also suggests that, if till texture was routinely reported, drumlins might consistently be associated with relatively sandy deposits.

Karrow's conjecture is only partly supported by evidence from the Union Streamlined Plain. The more subdued forms, those in the southeastern portion of the tract, are indeed composed of clayier till than that for more pronounced features elsewhere, suggesting the possibility that till texture is a controlling factor in height variation. But the relatively weak or statistically insignificant correlations between measures of drift texture and height, combined with the partial correlation analysis, which indicates that those correlations may be misleading, do not support such a substantive association. Moreover, if the down-ice and across-ice decline in feature height presents a genetically meaningful pattern, it implies some sort of controlling mechanism that is spatial in nature, perhaps some aspect of the ice itself.

Texture of the constituent till appears to exert a major influence on two basic attributes of the streamlined forms, elongation and asymmetry. A theoretical basis for the former was described by Chorley (1959, p. 343), who analyzed drumlin shapes and concluded that k-values appear to yield

> an inverse measure of the relative resistance presented by the equilibrium form...either because of the strength of the material itself or because of the low stress of the moulding medium, expressed in terms of the velocity of flow.

The correlations between till texture and k-value strongly suggest that the strength of the material may be a determining factor in feature elongation. Clearly, finer-textured tills are associated with more elongated forms. The areal distribution of k-values indicates that the rate of ice flow may have been important as well. Normally velocities are highest along the axis of a lobe and it is in the center of the tract (column E) that k-values tend to be greatest. Feature elongation in the Union Streamlined Plain, therefore, seems to be influenced in precisely the manner envisioned by Chorley.

Smalley and Unwin (1968) believe that clayey tills may be thixotropic and can, therefore, deform more easily than sandy ones. If correct, this may explain why coarser tills are associated with less elongated features; they simply are more difficult to mold into linear forms. Moreover, it may also explain why longitudinal asymmetry increases as till texture coarsens. As Chorley (1959) has pointed out, the more blunt the stoss end of a drumlin (and thus the less the stoss/lee ratio), the more streamlined is its shape. If sandy tills are indeed more resistant to deformation than clayey ones, a more streamlined shape may be required to allow the ice to flow over and mold them. This suggestion is consistent with the negative correlations between sand percentage and stoss/lee ratio (Tables 3, 5). Thus, both elongation and asymmetry, the two parameters most strongly correlated with till texture, exhibit properties compatible with the theoretical conjectures of Chorley, and Smalley and Unwin.

Everett (1976, p. 159) has questioned the validity of uncritically accepting interpretations of ice-flow direction when the inferences are based solely on drumlin asymmetry to denote the stoss (proximal) end. According to her

> Since so many drumlins do not have "perfect" shape, it is perhaps not a safe criterion upon which solely to base provenance of ice.

Based on the results of this study, her caution appears to have some merit. A majority of the asymmetrical features in samples A and B, 61 and 53 percent, respectively, have high points nearer the stoss end, but these relatively low values are certainly not definitive indicators. If ice-flow direction in the study area was not known independently, there could be some ambiguity, especially if only the features in sample B had been measured. Moreover, the statistical correlations and areal correspondence between till texture and longitudinal asymmetry suggest the possibility that regions with a more clayey till might exhibit a majority of asymmetrical forms with high points nearer the lee end.

Finally, the splaying pattern of the streamlined features, although not as pronounced as in some drumlin fields (Mills, 1980), indicates a diverging lobate flow during their formation. If, as is generally accepted, however, the Saginaw Lobe dissipated more rapidly than either the Lake Michigan or Huron-Erie lobes and was confined by them (Wayne and Zumberge, 1965), it is difficult to account for such a flow pattern. This suggests that either the Saginaw Lobe was more powerful than has been recognized or, prior to streamlining, the ice margin of one or both of the bounding lobes retreated a sufficient distance to allow divergent flow. If so, a later readvance by the Lake Michigan and Huron-Erie lobes would have formed the moraines bounding the streamlined forms on the east and west.

Conclusions

1. Streamlined topography associated with the Union Streamlined Plain is more widespread than previously mapped.

2. Relatively few of the streamlined hills within the tract fully exhibit "textbook" drumlin characteristics. Instead, a variety of forms ranging from drumlins through drumlinoid forms to indistinct flutings exist.
3. Two assemblages of streamlined landforms are present though their mutual boundary is amorphous. In the southeastern portion of the tract virtually all of the till landscape is smoothed and streamlined, the forms tend to be more subdued, and photolinear density is high. In the western part the streamlined hills commonly are more prominent and clearly separable from those nearby, photolinear density is lower, and streamlined and partially or non-streamlined hills are often juxtaposed.
4. The notable spatial pattern exhibited by several of the morphometric parameters may be genetically significant. In particular, the decrease in both feature elongation and photolinear density away from the central zones of the tract and, excluding the northeasternmost extension, the progressive down- and across-ice decline in feature height may be attributable to some characteristic of the streamlining ice.
5. The two measures of feature elongation, k-value and length/width ratio, are highly and significantly correlated but still exhibit differences in their association with other variables, some large enough to affect meaningful inferences.
6. The strong, statistically significant, and negative correlations between photolinear density and average feature height may be so functionally related such that increased erosion leads

both to greater photolinear density and lower streamlined hills.

7. Differences in till texture are clearly associated with variations in k-value and stoss/lee ratio. Correlations between these variables are statistically significant, are consistent with theoretical conjectures, and are believed to be causal.

8. The streamlining ice apparently carried differing amounts of englacial material—little in the southeastern portion of the tract, much more in the west.

9. Although both erosional and depositional processes apparently contributed to the formation of the streamlined hills, the former may have been predominant in the southeastern portion of the tract, the latter in the west.

10. The splaying orientation of the streamlined hills and photolinears indicates that either the Saginaw Lobe was more powerful than previously assumed or that, during drumlinization, it was laterally confined somewhat less than generally recognized.

CHAPTER III

SEDIMENTARY CHARACTERISTICS OF THE UNION STREAMLINED PLAIN

Introduction

Certain sedimentological properties of glacial deposits have long been recognized as providing valuable information about the geomorphic history of many areas. For example, the depth of carbonate leaching is one drift characteristic in humid regions that has been widely used to establish, or provide corroborating information on, the relative ages of numerous Pleistocene deposits (Dreimanis, 1957). Workers who have used these differences to distinguish between drift of the major glacial stages include Leverett (1909), Leverett and Taylor (1915), Alden and Leighton (1917), Leighton and MacClintock (1930), Kay (1931), and Thornbury (1940). Units of substage rank have also been differentiated by leaching depths (MacClintock, 1954; Forsyth, 1967; and Evenson and Mickelson, 1974) even though correlation or differentiation of drift units based on these measurements is a procedure fraught with difficulty (Flint, 1949).

In relatively recent times the concepts and procedures developed in the sub-discipline of stratigraphy have been more rigorously applied to Pleistocene deposits by some. As used in glacial geomorphology, rock-stratigraphic classification consists of the identification and delineation of drift units based on observable lithologic criteria. Fundamental attributes of these strata include a distinctiveness that allows recognition by commonly utilized procedures and a regional extent that can be traced laterally even though the lithologic characteristics may change gradationally (American Commission on Stratigraphic Nomenclature, 1961; Willman and Frye, 1970).

In some states of the Midwest, Illinois and Indiana in particular, rock stratigraphy has been used longer than in others. In Michigan, for instance, formal drift units have yet to be defined although informal ones have been utilized. Eschman (1978) delineated several and used "lithologic similarities" tentatively to correlate one of them with a till mapped in Ontario. A number of other sedimentological parameters have also been identified in the state. Perhaps the most useful to date involves data on clay minerals with the information being used to 1) differentiate deposits of juxtaposed lobes (Rieck, 1976; Lovan and Straw, 1978; Rieck et al., 1979); 2) distinguish between superposed till units (Taylor, 1983, for example); and 3) correlate till units exposed along the shore of Lake Michigan with moraines some distance inland (Gephart et al., 1983).

But in some places sedimentological properties of glacial till can be affected by local bedrock conditions (Gross and Moran, 1971; Rieck et al., 1979, for instance). And if this influence remains unrecognized, interpretations of the area's geomorphic history may be incorrect. Because the bedrock lithology and its depth vary markedly within and near the streamlined plain, the study area is an appropriate place for an investigation of such influence.

In this chapter the areal distribution and relationship to the bedrock surface of several sedimentological characteristics are examined: specifically, till texture, till fabrics, initial carbonate content, clay minerals, and depth of leaching.

Description of Bedrock Elevation and Lithology

The bedrock in most of the study area and nearly all of the Union Streamlined Plain is Coldwater Shale; Marshall Sandstone underlies the remainder (Figure 13). The bedrock-surface boundary between these two units trends approximately northwest-southeast and is just northeast of the streamlined tract. In the eastern portion of the study area the shale has relatively high elevations and in many places is at or near the surface. In the west it is much lower (Figure 14).

Rieck and Winters (1982) describe an imposing drift-buried escarpment, the Marshall Cuesta, which trends northwestward from near the state line until turning northeastward and then northwestward again (Figure 13). The bedrock surface elevations are lower and drift thicknesses much greater to the south and west. A second, higher escarpment (not shown) exists near the Coldwater/Marshall contact. The region between the scarps consists largely of a relatively level but dissected bedrock surface. This flat upland is underlain by the Coldwater Shale, a rock which exposures reveal to be relatively incompetent. Rieck and Winters believe that the shale-supported upland resulted from glacial quarrying of the once-overlying Marshall Sandstone and subsequent bevelling of the shale to produce the flat surface.

They also conclude that the southern escarpment and flat area were maintained without benefit of a caprock. There may, however, have been some lithologic control. Chung (1973) describes ironstone concretions concentrated near the top of the Coldwater formation that appear to be fairly widespread in this part of the state. Several near-surface layers of concretions are visible in the inactive Wolverine Portland Cement Quarry located in the beveled region between the two bedrock

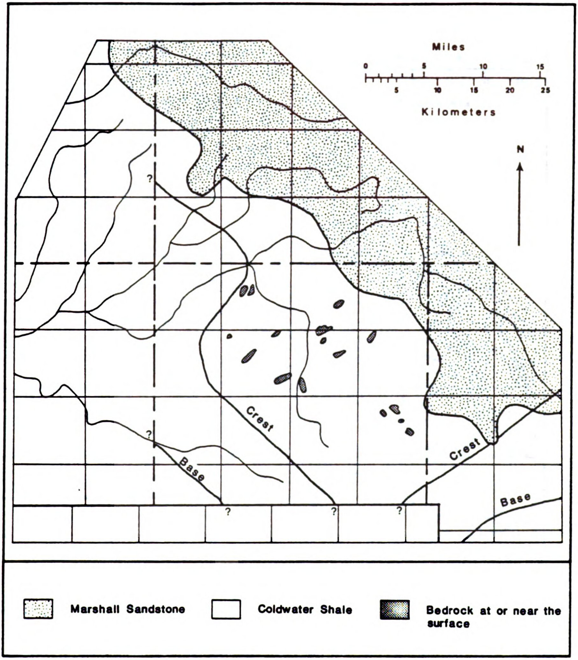

Figure 13. Bedrock lithology and base and crest of the Marshall Cuesta within the study area. Areas of bedrock at or near the surface are shown for Branch County. Sources: Rieck and Winters (1982), Rieck (pers. comm.), and Giroux et al. (1966).

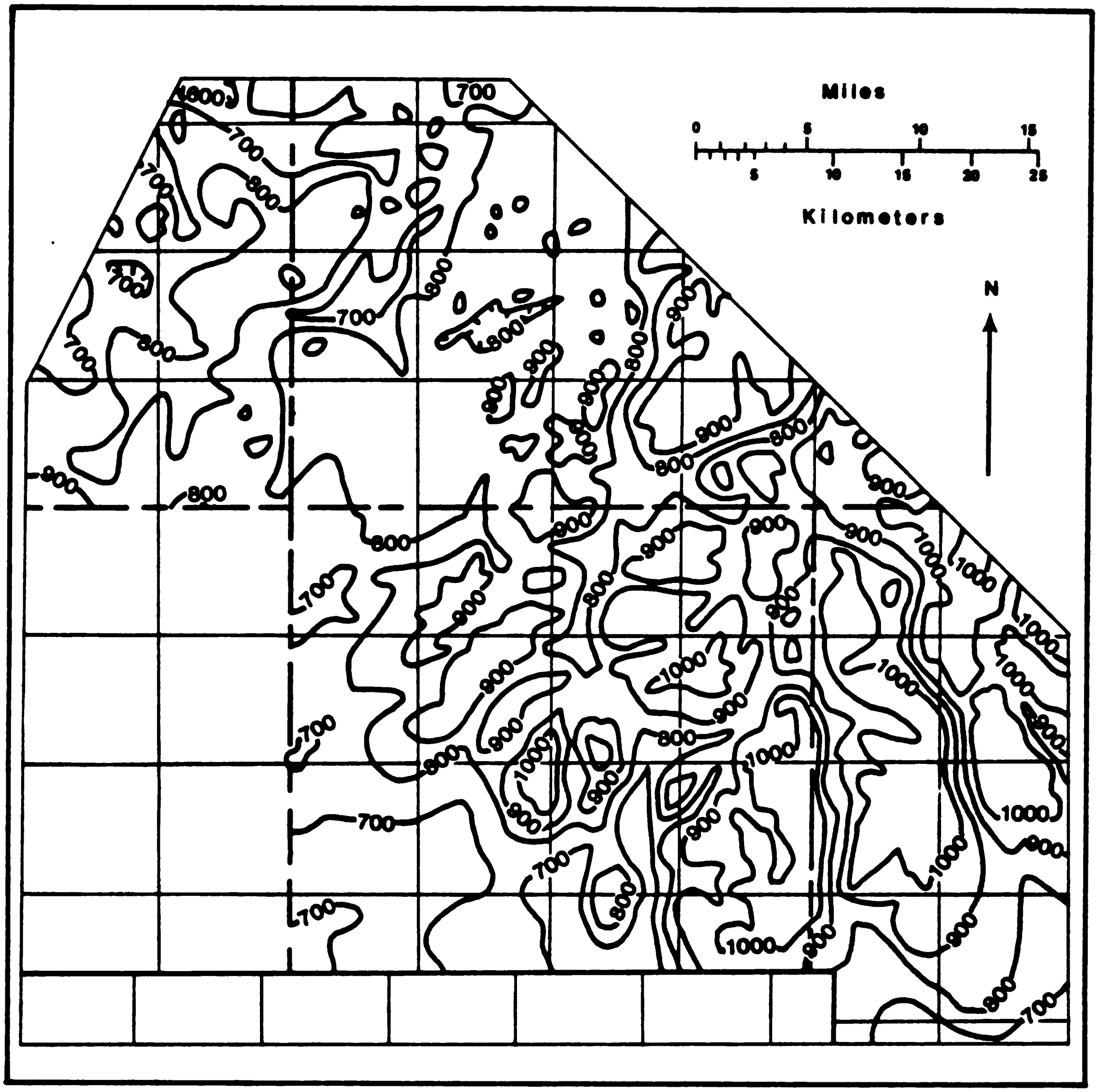

Figure 14. Bedrock elevations (in feet) within the study area. Source: Rieck (pers. comm.).

scarps (NW, Sec. 32, T. 6 S., R. 6 W.). These units are massive, continuous, and, when compared to the shale, resistant. They were found at only one other surface exposure but were encountered during augering at several locations. Moreover, pieces of the concretions, apparently from similar horizons, were found in the till throughout much of Branch County. If these units are as extensive as Chung (1973) presumed, they may have greatly retarded glacial abrasion and, in places at least, acted as a caprock, thereby allowing maintenance of the distal cuesta and flat upland described above.

Results

Till Texture

Percentages of sand, silt, and clay from till associated with drumlins and related landforms in the Union Streamlined Plain exhibit a distinctive spatial distribution. For each of the three textural components and with few anomalies, the area can be divided into two regions--one of higher, the other lower, values (Figure 15). And for all three textural classes in general, but for sand and silt in particular, the location of the boundaries between the regions is similar or coincident. Till in the southeastern portion of the tract is finer textured than that in the remainder. Moreover, for all three measures there is substantial variability in the former region, little in the latter.

The regionalization of sand, silt, and clay percentages is apparently related to bedrock elevation and lithology. The northeast-southwest-aligned boundary for all three textural components closely follows the course of the drift-buried lower crest of the Marshall Cuesta (Figure 15). East of this scarp the bedrock surface is

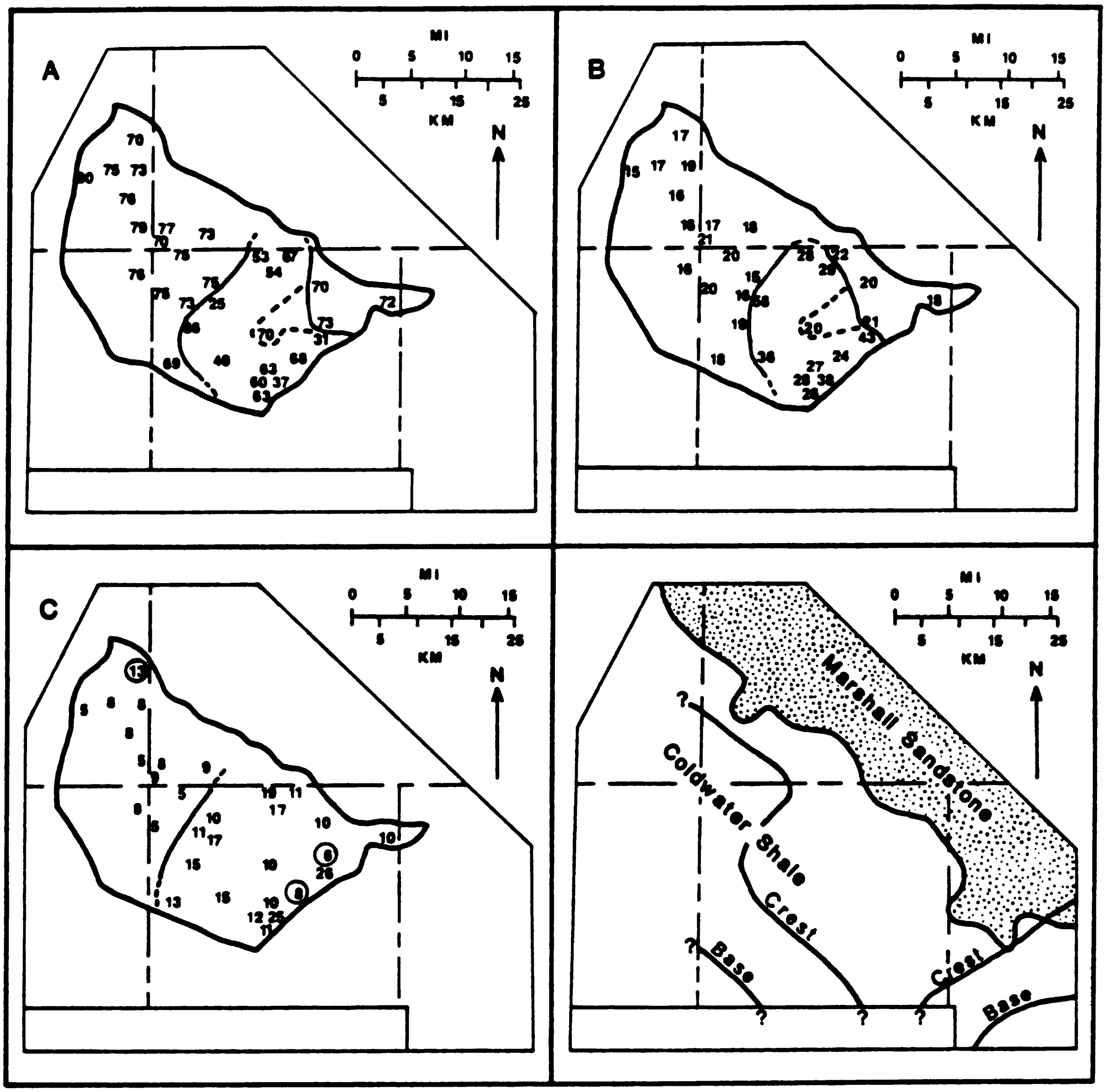

Figure 15. Percentages of sand (A), silt (B), and clay (C) for till samples within the Union Streamlined Plain. Separation into regions of higher and lower concentration is based on the following values: sand, equal to or greater than and less than 69%; silt, greater than and less than 23%; clay, equal to or greater than and less than 10%.

substantially higher, at or near the surface in places; the drift much thinner; and the till finer textured. Moreover, the till in the southeastern portion of the tract contains fragments of shale, and part of its matrix is commonly similar to weathered Coldwater Shale. But characteristics are different in the western part of the streamlined plain. Here, pieces of friable sandstone are often conspicuous.

In the northeastern portion of the drumlinized tract the general relationship between bedrock elevation and till texture is opposite from the rest of the area. Here, high bedrock elevations and relatively thin drift are associated with greater sand and lesser silt content (Figure 15). Because the bedrock surface boundary between the Coldwater Shale and the Marshall Sandstone is immediately up ice from this region, a major component of that till matrix may be derived from the latter unit. The influence of the Marshall Sandstone does not appear to extend very far down ice, however. Instead, a few kilometers from where the Coldwater Shale subcrops, its effect on till texture is pronounced.

Till Fabrics

Fourteen till fabrics determined in the Union Streamlined Plain have diverse patterns and orientations (Figure 16). Many have alignments similar to their corresponding feature, but some bear little or no resemblance. All were collected along or near the crest of these streamlined forms. None of the fabrics are unimodal, though a small number exhibit quite strong preferred orientations. Others display marked transverse components and one has a transverse maximum. Of those aligned in the general direction of their associated landform, up-glacier dips are predominant but not exclusively present.

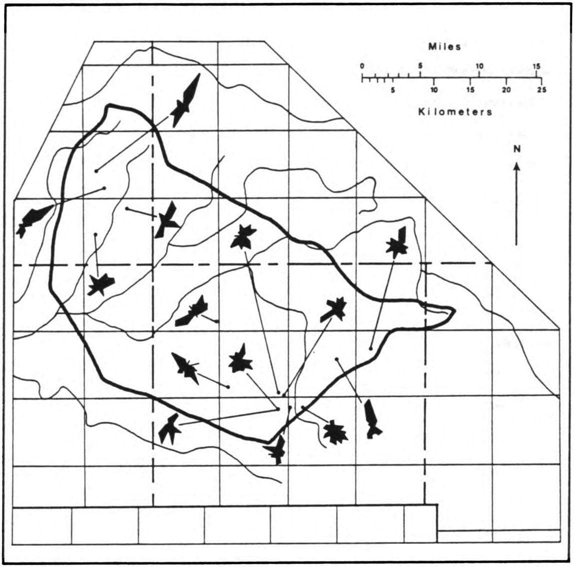

Figure 16. Rose diagrams for till fabrics within the Union Streamlined Plain.

Fabrics from the western portion of the tract tend to be more closely aligned with their respective forms and to have fewer, or less pronounced, discordant components. Many fabrics in the east, however, are characterized by more marked transverse or discordant modes, transverse maxima, non-alignment with their associated landform, or marked diversity in orientation over relatively short distances. Thus, preferred orientations of till fabrics and long-axis directions of streamlined hills tend to be more closely aligned for the higher forms, less so for the lower features.

Carbonate Content

Four measures of original carbonate content were determined: percentages of 1) calcite, 2) dolomite, 3) total carbonates, and 4) calcite/dolomite ratio. No apparent pattern or relationship was evident for the last one; but, as with measures of till texture, the others can be separated into two regions—one of higher, the other, lower, values (Figures 17, 18). And for all three, but for the latter two especially, the location of their boundaries corresponds rather closely with one another as well as with the divisions separating regions of differing sand, silt, and clay percentages (Figure 15). The southeast area has low carbonate content and is associated with finer-textured tills, thin drift, and high bedrock elevations. High carbonate content corresponds with the coarser till tract, irrespective of whether it is associated with the lower bedrock elevations and thicker drift in the western part of the tract or areas down-ice from the bedrock-surface boundary between the Marshall Sandstone and the Coldwater Shale.

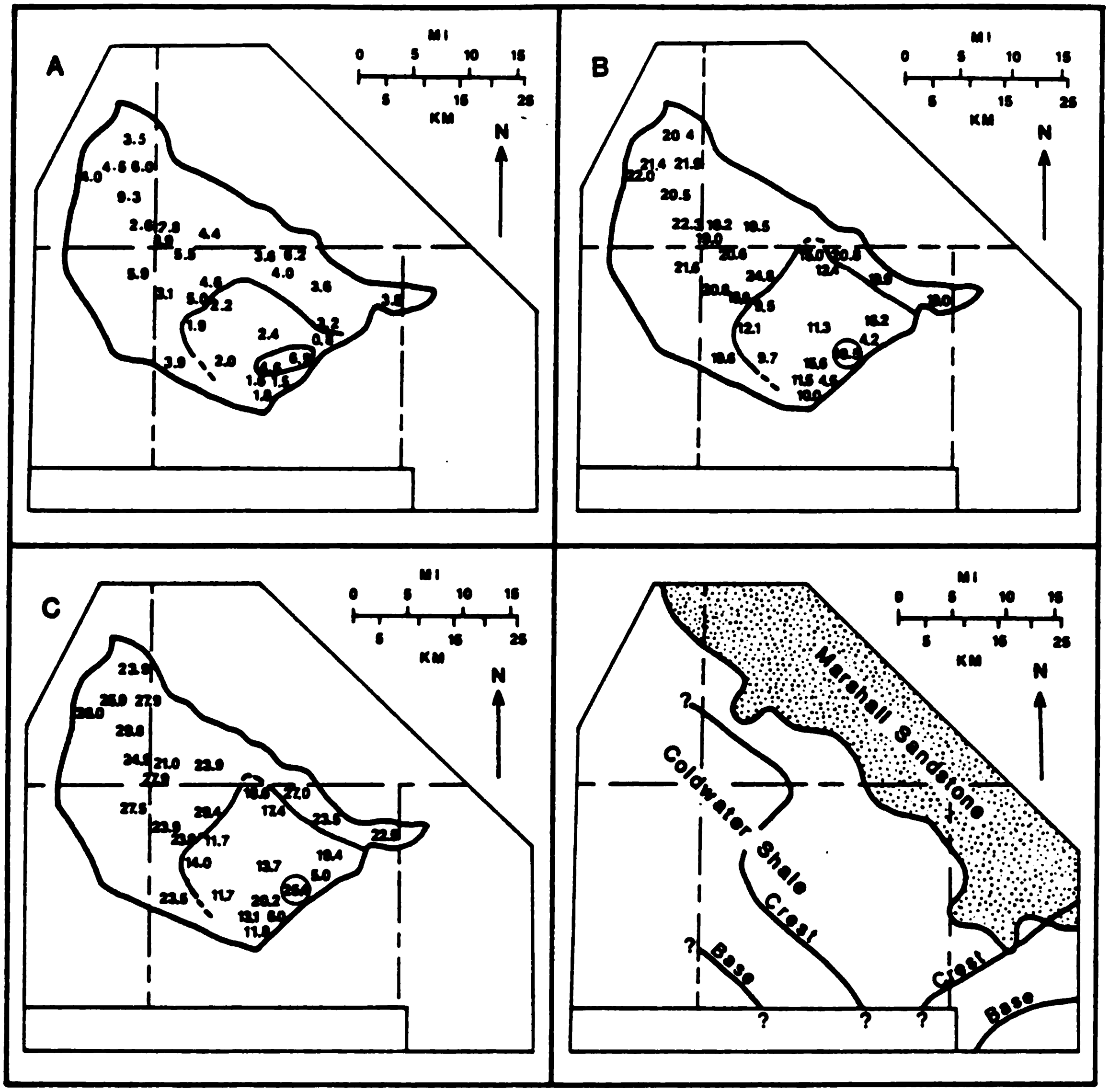

Figure 17. Percentages of calcite (A), dolomite (B), and total carbonates (C) for till samples within the Union Streamlined Plain. Separation into regions of higher and lower concentrations is based on the following values: calcite, greater than and less than 2.5%; dolomite, greater than and less than 17%; total carbonates, greater than and less than 20.5%.

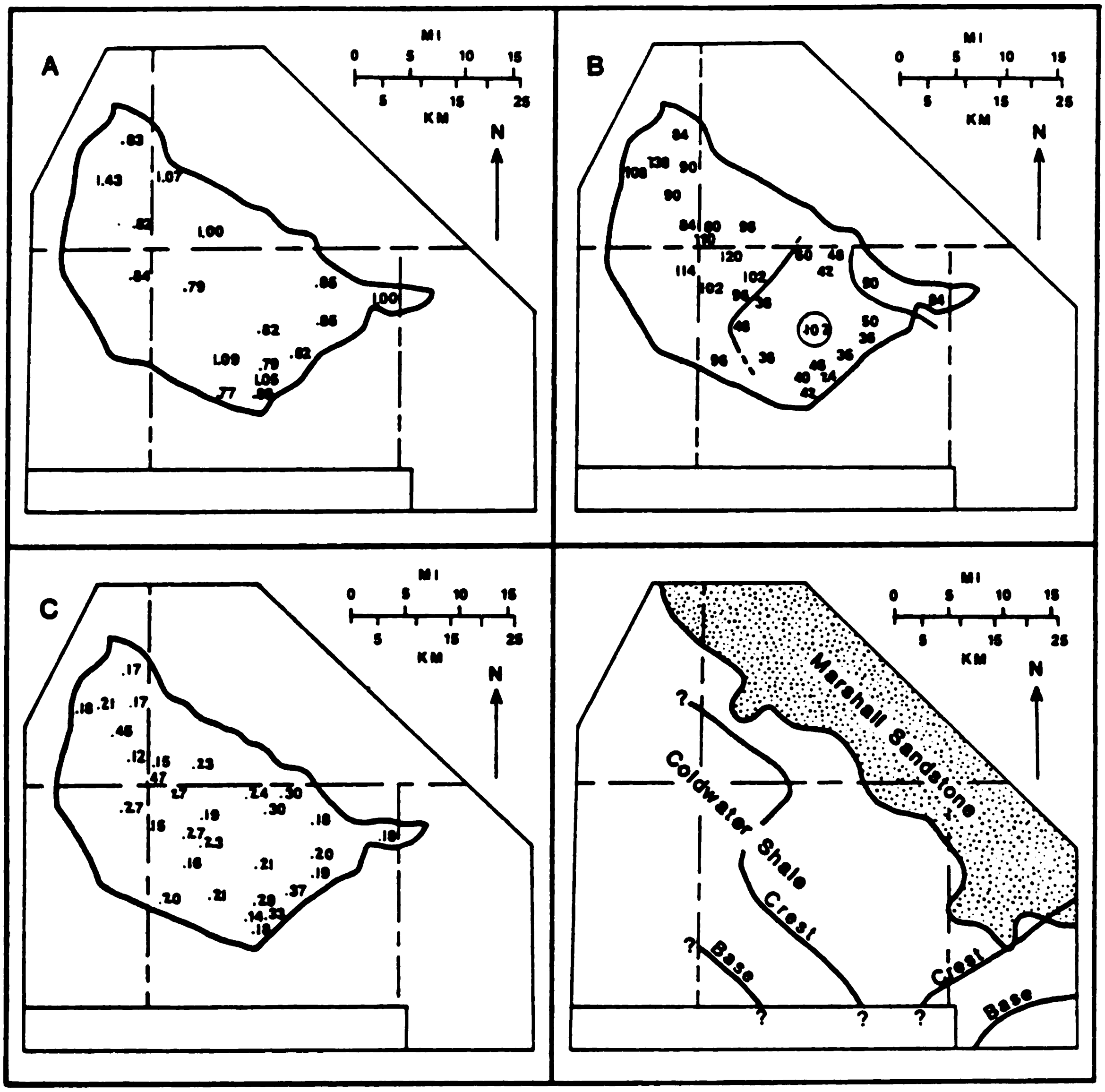

Figure 18. 7/10A clay mineral ratios (A), depth of leaching in inches (B), and calcite/dolomite ratios (C) for till samples within the Union Streamlined Plain. Separation into regions of deeper and shallower leaching is based on a value of greater than and less than 70 inches.

Near the study area, the upper part of the Coldwater formation is non-calcareous (Chung, 1973), a condition verified at several exposures and by numerous augerings. Thus, where this shale is a major component of the till matrix, the relative amount of carbonate is low. As with till texture, therefore, the areal relationships of carbonate measures with bedrock elevation and lithology should be a function of the erosion and incorporation of Coldwater Shale into the till matrix. This is precisely the situation in the southeastern portion of the tract. Higher carbonate contents elsewhere in the tract must be derived from some other source and, together with the lower silt percentages there, indicate substantially less, or no, inclusion of that shale.

Clay Minerals

Unlike till texture and carbonate percentages, no distinct pattern exists within the streamlined tract for the areal distribution of the 7/10A ratios of clay minerals (Figure 18). A wide range of values is present, from .77 to 1.43, but no areal differentiation. There may be a tendency for them to decline toward the southwest, however. Monaghan (1984) reports that the 7/10A ratios range from .99 to 1.61 for five till samples he examined within the northwesternmost portion of the streamlined plain.

Chung (1973) and Rieck (1976) have determined the 7/10A ratios for clay minerals from samples of the upper members of the Coldwater Shale collected in nearby Calhoun and Jackson counties, Michigan—the ratios 1.39 and 2.16, respectively. Given the proximity, these values are likely to be representative for the study area as well. And, because ratios for all but one of the till samples from the streamlined tract are substantially less than either bedrock sample, shale incorporation should have altered the clay mineralogy of the till in a predictable manner. Thus, increasing amounts of Coldwater Shale in the till matrix might be associated with higher 7/10A ratios. To assess this possibility, correlations between 7/10A ratios and silt percentages of samples were calculated--Coldwater Shale is dominantly composed of silt (Chung, 1973)--both for the area where conspicuous amounts of shale are incorporated in the till and for the other tract with little or no shale in the drift.

For the region with till rich in shale, the correlation coefficient between 7/10A ratios and silt percentage is quite strong, r= .793, and statistically significant. Thus, increasing shale content of the till is associated with higher 7/10A ratios. But for the remainder of the area, the coefficient is -.16, indicating that even if Coldwater Shale is a component of this till, its effect on the clay ratios is negligible.[1] Therefore, even though the area cannot be subdivided on the basis of 7/10A ratios and lacks the marked areal correspondence with bedrock demonstrated for till texture and measures of initial carbonate content, where there was substantial incorporation of Coldwater Shale into the till matrix, its effect on 7/10A ratios is still apparent.

Depth of Leaching

Preliminary fieldwork indicated that major differences in carbonate leaching existed across the Union Streamlined Plain; depths were shallow in the southeastern portion, deeper elsewhere. To more fully

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[1]Although the correlation coefficients change slightly, the above relationships hold irrespective of the group in which the possibly anomalous silt percentage site is included.

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document this pattern, many of the streamlined landforms were augered and the depth to free carbonates measured.

Field measurements for depth of leaching in samples ranged from .6 meters (23 inches) to 3.1 meters (120 inches); shallow depths in the southeast, deeper elsewhere (Figure 18). Moreover, with the exception of one site, the tract can be divided into regions of greater than and less than 1.8 meters (70 inches) leaching (Figure 18). The difference in leaching depths between the two regions is even more distinctive than it first appears. Only one location in the tract has a value between 1.3 meters (50 inches) and 2.1 meters (84 inches), and the zone along the areal boundary is not one of gradual transition from shallow to deeper leaching. Instead, it typically evidences substantial leaching differences over relatively short distances. Perhaps more importantly, however, the boundary separating these regions is similar or coincident to those dividing the regions of differing sand, silt, dolomite, and total carbonate percentages (Figures 15, 17). All of them, therefore, tend to follow the drift-buried lower crest of the Marshall Cuesta. Although the actual values differ, all of these relationships hold for carbonate corrected depths of leaching as well.

Shallow leaching depths are associated with the distribution of finer-textured tills, samples with lower carbonate contents, and areas of high bedrock elevations with thin drift. In contrast, deeper leaching is related to coarser till textures, drift with higher carbonate contents, and mostly places with thick drift and low bedrock elevations.

Discussion

Marked differences between the southeastern portion and the remainder of the Union Streamlined Plain exist for many characteristics of the surficial till. Texture, initial carbonate content, depth of leaching, and fabrics all exhibit this areal distinctiveness as well as a similarity or coincidence in the boundaries separating the contrasting regions. Based solely on these observations, one might reasonably infer that the deposits record the action either of two juxtaposed lobes or of two advances of the same lobe. Neither is believed to be the case.

In the former instance, the observed patterns would seem most easily explained by ice advancing from the east (Huron-Erie Lobe ?), with the sedimentological boundaries marking its perimeter. Streamlining by the Saginaw Lobe would occur sometime afterwards. But it seems too fortuitous to expect that the western and possibly southern borders of such an advance would coincide with the crest of the Marshall Cuesta instead of flowing over and down it. That is probably one of the least likely locations for an ice margin.

If the hypothetical second lobe came from the west instead (Lake Michigan Lobe?), the cuesta could serve as a topographic impediment of sufficient magnitude to halt or deflect its flow. That could possibly explain the southeastern versus western regionalization of drift characteristics, but not the circumstances in either the northeastern portion of the tract or along the southern margin of the Marshall Cuesta. In both instances an inordinate amount of shear in the advancing ice would be required for it to deposit the relatively sandy till in those two locations.

The second possibility, two advances of the same lobe, is also considered unlikely. Rieck and Winters (1982) have concluded that large amounts of Marshall sandstone were glacially quarried and the underlying Coldwater Shale beveled by abrasion in the southeastern portion of the Union Streamlined Plain. This is also the area of high bedrock elevation and thin drift (Figure 15). Furthermore, they cite Leverett (Leverett and Taylor, 1915; Leverett, 1918b) as reporting blocks of that sandstone, much of it angular, in the surficial drift of Branch County down-ice from the subcropping Marshall-Coldwater boundary. Because the presence of these rocks at the surface would be difficult to explain otherwise, at least some of the quarrying and beveling must have taken place during the Woodfordian. Thus, the till overlying the shale "uplands" in the southeastern part of the tract must also be that age.

Because bedrock elevations are much lower and the drift quite thick in the western part of the streamlined plain, glacial erosion down to the Coldwater Shale bedrock may not have occurred during the Woodfordian. A pre-last-advance till sheet could, therefore, be present at depth though none has yet been recognized. Several circumstances, however, indicate that the surficial till in general, and that comprising the drumlins and related forms in particular, is of Woodfordian age. The streamlined hills there were formed during that time and their morphological characteristics indicate that they are depositional features (see Chapter II). Moreover, pieces of Marshall Sandstone are near the surface of many of the landforms. The friable nature of these stones suggests that they would not withstand repeated glaciation or long periods of weathering. Thus, throughout the tract the surficial till and streamlined topography are believed to be of Woodfordian age.

The spatial distribution of surficial till characteristics within the streamlined tract seems adequately explained by the action of the Saginaw Lobe traversing this region of differing bedrock elevation and lithology. Where Coldwater Shale is high in the landscape and near the surface, it was eroded to become a noticeable component of the till a short distance down-ice from where it was removed. Where low and relatively far beneath the present surface, its incorporation into the surficial drift was minimal or nonexistent. These circumstances demonstrate a local origin for much of the till matrix in the southeastern portion of the Union Streamlined Plain.

The marked influence of local bedrock characteristics upon overlying till has been recognized in a number of other places as well. For example, Goldthwaite (1971, p. 14) notes that "Shales produce a constant quantity of small fragments in the till immediately above the outcrop..." Similarly, Gross and Moran (1971) demonstrated a striking correspondence between bedrock lithology and several components of the superjacent till in an area where the ice had been eroding across a lithologic boundary. In those areas where the till did not reflect the changes in bedrock, they concluded that deposition, not erosion, had taken place. Still other locations where local bedrock was the dominant factor determining major characteristics of the overlying till are reported by Aario, Forsstrom, and Lahermo (1974) and Krall (1977).

If, as believed, the surficial till comprising the streamlined hills records the action of a single glacial lobe, then the areal differentiation of its lithologic characteristics represents two distinctive facies of the same till unit. Clark and Karrow (1983, p. 1316) examined relationships between local bedrock and several till parameters in the St. Lawrence Valley and report a similar circumstance. Referring to specific properties of the till including texture, initial carbonate content, and depth of leaching, they state that the areal differences "can be directly attributed to the influence of the underlying bedrock...and these changes are interpreted as facies variations within one till sheet." Perhaps as important, they, too, found that calcite/dolomite ratios were not noticeably affected by changes in the subcropping bedrock. To the extent that this circumstance is common and widespread, it may be that these ratios, or ratios in general, are minimally altered by local bedrock conditions. Therefore, they might be preferable rock-stratigraphic indicators in regions where the influence of local bedrock is substantial.

Boulton (1979, p. 35) has proposed that two principal styles of glacial erosion exist

> (a) where the substratum is relatively resistant compared with glacial ice and is composed of cohesive material; (b) where the substratum is relatively deformable compared with glacial ice and is of low or zero adhesion. In (a), fragments of that substratum are eroded by inclusion and transported within the glacier. Long-distance transport is possible. In (b), it is eroded primarily as a result of deformation beneath the glacier. Long-distance transport is unlikely.

I believe that the effects of both are visible in the streamlined plain. The boulder-sized igneous and metamorphic erratics which are common in the till here are obviously far-traveled. Their most likely source is Michigan's northern peninsula or adjacent regions of Canada. If Boulton is correct, this material must have been carried englacially for the most part.

In contrast, glacial erosion in the southeastern portion of the tract has produced a till matrix closely reflecting the lithologic character of the local bedrock. And much of that material was apparently deposited within a relatively short distance from where it was removed. The changing effects of the bedrock would not be so noticeable otherwise. This would be true even if the till had been deposited pre-last-advance and then exposed by erosion during the Woodfordian. A large part of the drift here seems to have been transported in the second manner, that is, by deformation below the base of the ice. This mechanism does not require the change in glacial regimes (from eroding to depositing) that others seemingly imply. And because the Coldwater Shale is a relatively incompetent rock, its removal could presumably be accomplished in this manner. Moreover, since this process is not as powerful an erosive agent as the former, it may help explain how the "soft" shale, probably in conjunction with the concretionary layers described earlier, was able to maintain a high elevation.

This explanation is also compatible with the assertion that the till overlying the shale "uplands" is not pre-Woodfordian. And it may in part account for the anomalous till fabrics in this portion of the streamlined tract. As described by Boulton (1979, p. 31), large boulders will affect deformation of the till beneath the base of the ice such that "the coarser parts will tend to deform less rapidly than other parts, will block movement of material on their up-glacier sides, and thus produce transverse flow components..." In this view, the deforming drift sometimes moves in a direction somewhat independent of the ice above. It, therefore, seems likely that till fabrics associated with such sediments might exhibit a variety of orientations not aligned with the movement of overriding ice.

If this explanation is correct, the suggestion by Dodson and Winters (1977) that some of the anomalous fabrics might record a pre-streamlining advance of the Huron-Erie Lobe into the tract seems precluded. The conclusion herein that all of the till in the streamlined plain is associated with the Saginaw Lobe is also inconsistent with that conjecture.

Within the Union Streamlined Plain preferred orientations of till fabrics and long-axis directions of streamlined hills tend to be more closely aligned for the higher forms, less so for the lower features. Working in Finland, Aario, Forsstrom, and Lahermo (1974) also found differing alignments related to height. But there the relationship is reversed; lower, not higher, features tend toward correspondence. Irrespective of the cause, such variability attests to the desirability of using multiple fabrics when determining direction of ice flow, a caution advocated by Kauranne (1960) and Young (1969) for similar reasons.

Conclusions

1. Within the Union Streamlined Plain, percentages of sand, silt, clay, calcite, dolomite, and total carbonate of the surficial till, as well as leaching depths, exhibit marked differences between the southeastern portion and the remainder of the tract. And for all of these parameters, the location of the boundary separating the two regions is similar or identical.
2. Two distinctive facies variations are interpreted for the till unit. They are a function of bedrock elevation and lithology.

3. Much of the till matrix in the southeastern portion of the streamlined plain is of local origin.
4. Throughout the tract, most of the cobble- and larger-sized component of the till has a distant origin.
5. Of the till properties examined, calcite/dolomite and 7/10A ratios were the least affected by local bedrock conditions. Therefore, they may be best suited to characterize rock-stratigraphic units in areas where the local bedrock constitutes a substantial portion of the till matrix.
6. In the southeastern portion of the tract, erosion of the shale bedrock and transport of the till appear to have been accomplished largely through deformation in that part of the drift below the base of the ice.
7. The influence of local bedrock conditions should be carefully considered when interpretations of glacial history are based solely or largely on lithologic properties of the till. Ignoring it could lead to erroneous conclusions.

CHAPTER IV

A REEXAMINATION OF MORAINIC AREAS BOUNDING THE UNION STREAMLINED PLAIN

The Sturgis Moraine

The Sturgis Moraine extends southeastward from an interlobate tract just west of the study area to the vicinity of Orland, Indiana (Figures 1, 2). Leverett (Leverett and Taylor, 1915) divided the moraine into two sections, a main portion whose distal margin is marked by an outwash apron and a more proximal part consisting of a series of discontinuous segments. The latter appear to have been delineated mainly on the basis of elevation and the presence of boulders. Based on several exposures, drift in the moraine is coarse textured, and flow till interbedded with sands and gravels is common.

Several gaps bisect the main portion of the moraine. Also present are distinctive channels, but these do not completely cross both the moraine and distal outwash plain. Two of the latter, situated just north of Sturgis and centered in Sections 22 and 25, T. 8 S., R. 10 W., are noteworthy. Neither has through-flowing drainage, but both have steep-walled sides and are aligned with nearby northeast-southwest-trending lakes and streams. These channels can perhaps best be described as box-canyon valleys. Such characteristics are similar to hydrographic conditions elsewhere in Michigan described by Rieck and Winters (1976) and suggest the former presence of buried ice in a bedrock or pre-last-advance valley.

Small areas of poorly developed streamlined topography that are part of the Union Streamlined Plain exist on the proximal side of the Sturgis Moraine's inner segments (Figures 3, 4). The boundary between these and the moraine lacks a clear topographical expression, however. Its precise location, therefore, is uncertain.

Tekonsha Moraine of the Saginaw Lobe

General Description

Leverett (Leverett and Taylor, 1915) described the Tekonsha Moraine of the Saginaw Lobe as being relatively prominent along most of its course. It can be traced from the town of Quincy, where it trends northward, and thence generally northwestward to the Kalamazoo River to join its Lake Michigan Lobe correlative (Figures 1, 19). Local relief is commonly 6 to 9 meters (20 to 30 feet), but both flatter areas and hills more than 30 meters (100 feet) high are also present. Crest elevations decline to the northwest and range from about 335 meters (1100 feet) near Quincy to 297 meters (975 feet) just south of the Kalamazoo River. Several valleys cross the moraine, the most conspicuous being that of the St. Joseph River.

Inspection of numerous exposures and randomly located auger borings revealed marked differences in drift composition between the eastern and western portions of the moraine. In the east till and large boulders are common, but toward the west sand and gravel predominate. This generalization is supported by the inferred parent material for soils mapped on the feature. In Branch County the Hillsdale series, a soil developed on till, is extensive (Moon and Wildermuth, 1928). Two soils, Coloma and Bellefontaine, predominate in Calhoun County (Rodgers and Smith, 1919). The former is mapped east of Nottawa Creek, the latter to its west. The Coloma series forms on till, but Bellefontaine may develop on either sand and gravel or till parent material (D. Mokma, pers. comm.). Although

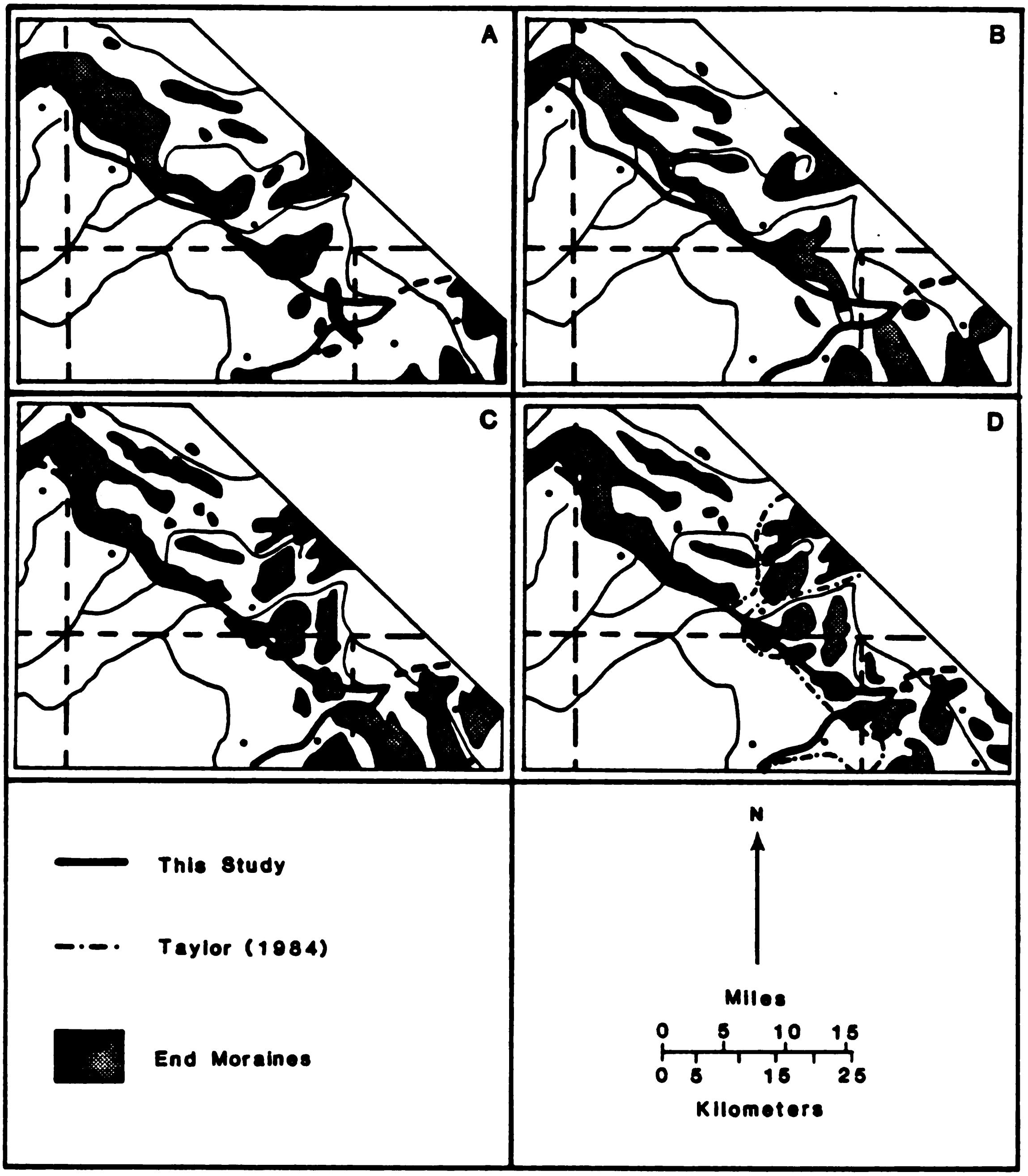

Figure 19. The Tekonsha margin of the Saginaw Lobe as interpreted herein and depictions of the moraine by various workers: Leverett, 1915 (A); Leverett, 1924a (B); Martin, 1955 (C); Farrand, 1982 (D). See text for explanation of Taylor's boundary.

originally classified as the Bellefontaine series (Perkins and Tyson, 1926), mineral soils on the moraine in Kalamazoo County are now mapped as Oshtemo and Spinks, both of which develop on sand and gravel (Austin, 1979). This situation suggests that in western Calhoun County much or all of the soil mapped as Bellefontaine also probably formed on sand and gravel. These multiple lines of evidence demonstrate that the drift comprising at least the surficial portion of the Tekonsha Moraine of the Saginaw Lobe contains appreciable amounts of till in its eastern half, but to the west sand and gravel are predominant.

The change in drift composition of the moraine is accompanied by landform differences as well. Kettles, outwash plains and aprons--both within and distal to the moraine--kames, and eskerine forms all suggest large-scale ice stagnation in the west. These features are either lacking or much less common in the east and imply a somewhat different mode of deglaciation. The division between these two regions is not abrupt, however. In fact, the portion of the moraine near the St. Joseph River exhibits landforms from both assemblages. Streamlined hills exist along most of the feature's length and will be discussed later in this chapter.

Reinterpreted Location of the Former Ice Margin

Along much of its distal margin the Tekonsha Moraine of the Saginaw Lobe is so distinctive that previous workers have mapped it similarly or identically. The most notable differences are near and east of the Kalamazoo/Calhoun County border and at its easternmost limit (Figure 19). As interpreted here, the western portion of the margin is essentially the same as that shown by Martin (1955), Farrand (1982), and

Taylor (1984). But along some of its course differences between this and previous interpretations are marked (Figure 19).[1]

As mapped herein, the Tekonsha margin near Allen is either east or north of placements by Leverett (Leverett and Taylor, 1915; Leverett, 1924a), Martin (1955), Farrand (1982), and Taylor (1984) (Figures 1, 19). That the Saginaw Lobe extended this far east is demonstrated by the narrow northeasternmost extension of the Union Streamlined Plain. Quite prominent drumlins and related forms here show no evidence of post-formation glacial modification (see Chapter II). Johnson and Keller (1972), apparently the only workers previously to recognize these features, map them as far east as Jonesville, an assessment with which I concur.[2] But the easternmost of these linear forms are not clearly expressed, and associated hummocky topography indicates overriding by ice of the Huron-Erie Lobe. Proximal to the Tekonsha margin in this region is subdued morainic topography associated with still other streamlined hills (Figure 20). The contact between this morainic area and the Union Streamlined Plain marks the Tekonsha margin; and Soap Creek, some of whose course may represent a fosse stream, follows it for a short distance.

Several kilometers west of Tekonsha a large kame, Dixon Hill, marks the former position of the ice margin. Its surface generally lacks boulders or large cobbles and, based on sediments exposed by a

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[1]Taylor (1984) has suggested that a major reentrant may have developed along the ice margin. His proposed placement is shown on Figure 19 but a discussion of it is beyond the scope of this study.

[2]The map of Johnson and Keller (1972) terminates just south of the Tekonsha margin here delineated. Their interpretation of its placement is, therefore, uncertain.

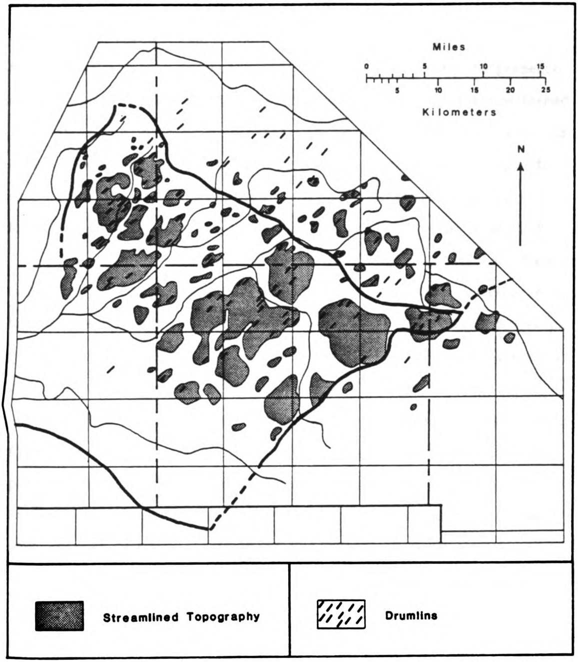

Figure 20. Drumlins, areas of streamlined topography, and significant ice-marginal positions within the study area.

sand-mining operation, is composed of sand with an overlying gravel horizon. An esker joins the hill at its ice-contact, proximal border. The less steep but still considerable slope on the kame's distal side has several spurlike irregularities which, together with the presence of the nearby Union Streamlined Plain, suggest that the feature formed just within the ice margin and that some meltwater associated with its formation drained subglacially. Otherwise, it would be difficult to account for the relatively steep distal slope. Taylor (1984) states that, though its origin is debatable, the hill may be a "kame fan."

Less than three kilometers to the southeast is a distinct "head of outwash." Though possibly oversteepened and accentuated by erosion from the St. Joseph River, it too appears to mark a significant ice-marginal position. As the elevation of this outwash surface declines distally, the crests of progressively better expressed streamlined hills are revealed, thereby indicating different degrees of burial by the glaciofluvial sediments. These landforms, therefore, are properly included as part of the Union Streamlined Plain (see Chapter II). Martin (1955), Farrand (1982), and Taylor (1984), however, show the northeasternmost part of this feature to be part of the Tekonsha Moraine.

Between Nottawa Creek and the Kalamazoo/Calhoun county border the former location of the ice margin is especially difficult to interpret, and previous workers differ greatly in their placements (Figure 19). The terrain in this area is covered predominantly by glaciofluvial sediments, and these accumulations of outwash are widespread both within and distal to the morainic area. They are not all part of the same landform, however; elevation relationships indicate several episodes of deposition, each with a different source area. Small kames, crevasse filling or eskerine features, ice-contact slopes, and kettles or lowlands marking positions of former buried ice masses are also present. Exposures of till are rare, but flow till can be found as thin layers interbedded with sands and gravels in some of the kames.

The distalmost former position of the ice border here is revealed largely by a "head of outwash" although other characteristics, such as the presence of boulders, augment the interpretation. But because the placement inferred by previous workers differs markedly at some places, perhaps they used different criteria to locate it (Figure 21). Or, possibly, the dissimilarities may have resulted from inadequate detail on the less accurate, smaller-scale topographic maps available to them. This would seem especially likely here because portions of the landscape are quite complex.

Associated Streamlined Features

Drumlins and other streamlined landforms exist proximal to the Tekonsha margin of the Saginaw Lobe (Figure 20). Shah (1971) is apparently the only previous worker to have noted their presence, and he neither described nor located any of the features beyond stating that they are present on "top" of the moraine. But his study was concerned primarily with Kalamazoo County. I have found that they exist in portions of Calhoun, Branch, Hillsdale, and Jackson counties as well.

Many of these streamlined hills are quite prominent and are properly termed drumlins. They are elongated generally northeast-southwest, but a splaying pattern exists which corresponds to that in the adjacent Union Streamlined Plain (see Chapter II). Thus, for any presumed flow line, the streamlined hills on both sides of the Tekonsha margin exhibit

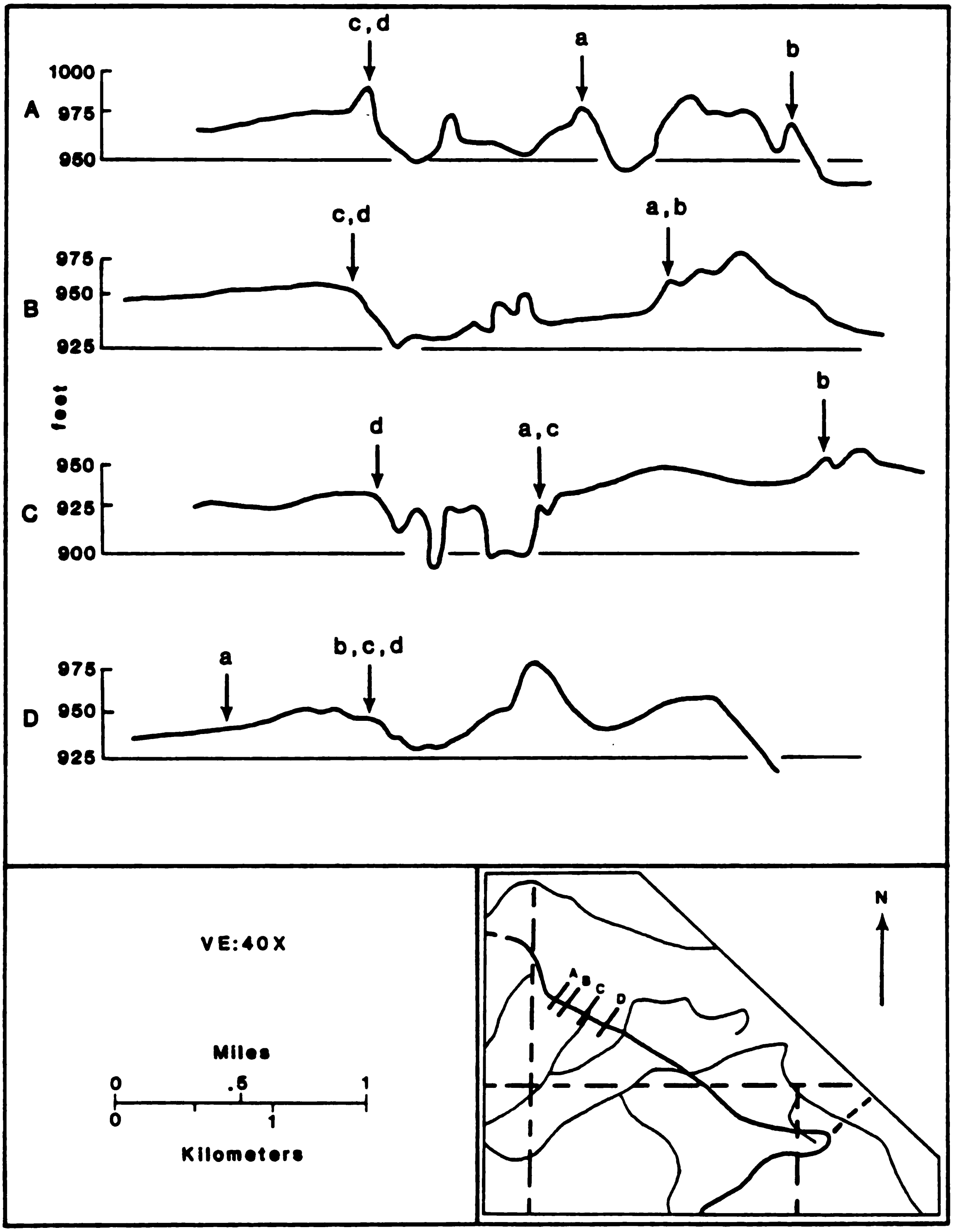

Figure 21. Topographic profiles across the western portion of the Tekonsha Moraine showing the placement of its distal margin by various workers: Leverett, 1915 (a); Leverett, 1924a (b); Martin, 1955 (c); this study (d).

similar azimuths. Some of the poorly developed features in the far eastern part of the moraine have such a bend in their long axis such that the distal portion trends in a more southerly direction than the rest of the form. Elongated hills which do not appear streamlined are also present locally.

Road cuts or randomly-located auger borings in many of the streamlined hills show that they are composed of till. Many west of Tekonsha are surrounded by outwash deposits, a situation recognizable by the topography and the distribution of surficial boulders (present on the streamlined hills but absent on the surrounding, lower terrain). In contrast, the drumlins and related forms to the east generally have till adjacent to them. Deposits of sand and gravel exist high in the flanks of several of the streamlined hills; others have substantial accumulations of till superimposed on them. Thus, in several important respects, the streamlined hills associated with the moraine exhibit characteristics similar to the features in the western portion of the Union Streamlined Plain (see Chapter II).

Formation of the Tekonsha Moraine and Associated Streamlined Features

The presence of drumlins and related landforms associated with the Tekonsha Moraine of the Saginaw Lobe poses some important questions concerning the relationship between these streamlined hills, those in the Union Streamlined Plain, and the moraine. Specifically, 1) was all of the drumlinized topography formed at approximately the same time, or does it record two episodes of streamlining? And 2) if the former, did streamlining occur before, during, or after the formation of the moraine?

Two separate drumlinizing advances by the same lobe at virtually the same place would seem to be unusual, especially here because there are apparently no other tracts of streamlined landforms in the southern portion of Michigan's southern peninsula (Bergquist, 1941a). Moreover, if there were two advances, where is the margin for each? Clearly, one is near the distal border of the Union Streamlined Plain, presumably either the main portion or the discontinuous inner member of the Sturgis Moraine. But evidence for another is lacking. Furthermore, none of the drumlinized topography within the Union Streamlined Plain exhibits any evidence of modification by glacial overriding. Nor is there any indication of an ice-marginal position within the boundaries of the tract.

The Tekonsha margin of the Saginaw Lobe could conceivably mark the limit of a second drumlinizing advance. But in some places the streamlined forms associated with the moraine extend up to or very near that border, and active-ice landforms such as these are not reported to form so close to an ice margin. Instead, they develop some distance proximal to the border (Menzies, 1978/1979). Thus there is no sound evidence for a second drumlinizing episode, indicating the likelihood that all of the streamlined features are associated with one period of formation.

Given the temporal similarity of the streamlined landforms, what is their relationship to the moraine? Bergquist (1941a) suggested that the Union Streamlined Plain was produced by a readvance of the Saginaw Lobe after it had formed the Tekonsha Moraine. If the moraine had been overridden, however, the higher areas should be "stretched in drumlin fashion..." as proposed by Totten (1969, p. 1936). But many are not. Rather, no consistent elevation relationship exists between height and the presence of streamlining. In fact, the highest hill on the moraine is not elongated.

More important are the topographic relationships between streamlined and non-streamlined components of the moraine. At several locations drumlins on the moraine have accumulations of till extending from them or have stratified sand and gravel deposits high on their flanks. Both circumstances demonstrate post-streamlining deposition, though not necessarily a separate glacial advance. Perhaps most instructive, however, is the fact that the distal border of the western portion of the Tekonsha Moraine is marked by a notable "head of outwash." It would seem impossible for a drumlinizing ice advance to override this margin to produce the streamlined forms yet leave this feature undisturbed. These observations demonstrate that streamlining preceded formation of the moraine.

Clay mineral data for samples from six sites along the moraine show differences in 7/10A ratios between streamlined and morainic hills; the former have higher values than the latter, 1.07, 1.13, 1.14, and 1.27 versus .95 and .96, respectively (Figure 22). Although their limited number make this differentiation somewhat tenuous, the fact that the locations were from along the length of the moraine lends some credence to their validity. Till fabrics also show differences between the drumlins and morainic hills. Those from the former are aligned with the long axis of their associated features, but those from the latter exhibit various orientations (Figure 22).

Exposures in the streamlined hills within the moraine are rare, but none of those examined revealed 1) superposed basal tills, 2) till other than flow till overlying glaciofluvial sediments, or 3) struc-

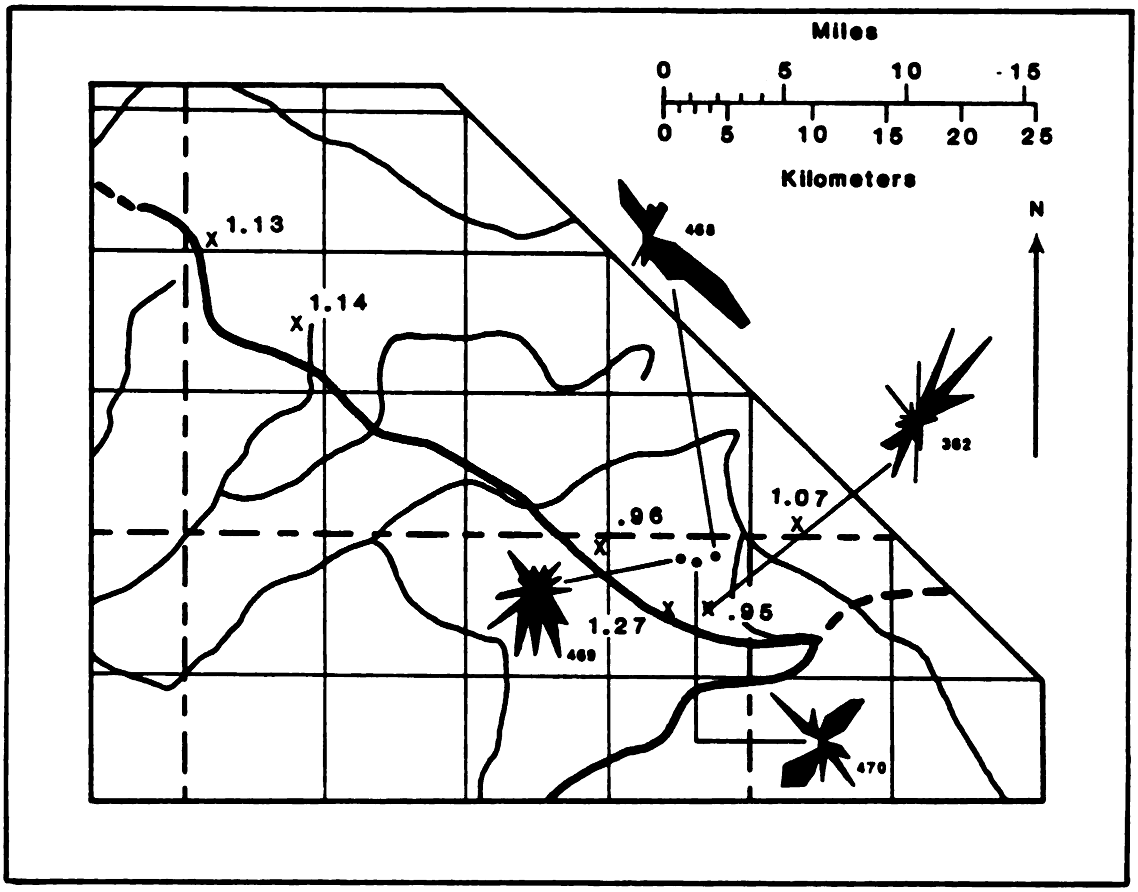

Figure 22. Till fabric diagrams and 7/10A ratios of clay minerals from streamlined and morainic hills associated with the Tekonsha Moraine of the Saginaw Lobe.

tures, such as convolutions or shearing, indicative of overriding ice. Thus both topographic and sedimentologic characteristics indicate two separate depositional episodes, but there is no direct stratigraphic evidence for a readvance.

Leverett (1924b), Bergquist (1941b), and Zumberge (1960) suggested that, following a substantial retreat of its ice front, the Saginaw Lobe readvanced to the position of the Tekonsha Moraine. But I have discovered no exposures demonstrating such an overriding. If they are correct, therefore, the streamlined hills associated with the moraine were apparently "protected" in some manner, possibly by stagnant ice. In the western portion of the moraine there are numerous lowlands produced by the burial of ice blocks, but they could have resulted either from a readvance or from a periodic recession of the ice front. The former circumstance, however, presumably would reactivate some of the stagnant ice. To the east, those few streamlined features with a bend in their long axis may represent such a reactivation. Alternatively, they could merely record a local realignment of ice flow associated with building of the moraine. Thus the evidence is ambiguous. Perhaps the Saginaw Lobe did experience a substantial readvance to the Tekonsha margin. And perhaps it did not.

Formation of the Moraine

All of these conditions are compatible with the following sequence of events: 1) the advancing Saginaw Lobe streamlined the terrain throughout much of the study area; 2) its margin subsequently withdrew to at least the position of the Tekonsha Moraine, and possibly much farther; 3) the Saginaw Lobe experienced a stillstand at the Tekonsha margin, perhaps after readvancing to that position; 4) glaciofluvial landforms associated with the moraine were deposited; and 5) final deglaciation of the study area left the morainic topography and associated streamlined features largely as visible today.

A Reinterpretation of the Lake Michigan Lobe Tekonsha Moraine

General Description

As applied in the United States, the term moraine connotes "an accumulation of drift deposited chiefly by direct glacial action, and possessing initial constructional form independent of the floor beneath it." This use differs from that in parts of Europe where the word is often synonymous with till (Flint, 1971, p. 199). Morphology, therefore, not sedimentary character, is the primary descriptive attribute. Morainic topography can be produced in a number of ways, however, not all of them by direct glacial action. Evidence will be presented here that much of the Tekonsha margin of the Lake Michigan Lobe, although exhibiting morainic topography, does not fully conform to the above definition. Because of previous usage and for purposes of discussion, the term "moraine" will be retained, but it should be recognized that it may not exactly fit the generally accepted North American definition.

Various locations for the southern limit of the Tekonsha Moraine of the Lake Michigan Lobe have been proposed. This discussion, however, will concern itself only with that portion of the landscape north of Scotts, Michigan (Figures 1, 4). There the moraine is bounded on both sides by sand and gravel. To the east, in the reentrant between former positions of the Saginaw and Lake Michigan lobes, is the southwestward-sloping Climax-Scotts Outwash Plain. Sediments associated with this feature also become finer in that direction (Shah, 1971). West of the moraine is the topographically lower Galesburg-Vicksburg Outwash Plain. In places this moraine-outwash plain border is marked by distinctive bluffs up to 9 meters (30 feet) high. Most of the morainic surface is quite hummocky, knolls and basins are common, and much of the landscape is in slope.

Sedimentary Characteristics

Till is largely absent in the moraine. Sediments exposed in gravel pits, in road cuts, and by numerous auger borings show that the near surface portion of the feature is composed predominantly of glaciofluvial deposits. A recently completed soil survey supports this conclusion; all mineral soils mapped on the moraine are believed to have developed on sand and gravel parent material (Austin, 1979). Moreover, Leverett (1919b) noted that, although the moraine is traversed by the Portage River, no streams rise within it, a condition he interpreted as consistent with the presence of coarse textured sediments. All of these observations indicate that the morainic landscape is composed mostly of stratified drift.

Augering at many places revealed about one-half meter, sometimes more, of a non-calcareous, sandy and clayey sediment overlying the sands and gravels. Where present they comprise a two-storied soil in the pedologic sense. Lovan and Straw (1978) apparently interpreted the upper horizon as a basal till and used it to characterize the 7/10A clay mineral and garnet/epidote ratios of till in the moraine. Monaghan (1984) may have interpreted it in a similar manner. For the following reasons, however, considering the upper unit to be a till is questionable: 1: it is areally discontinuous and, though cobbles are locally associated with it, large boulders are absent except on the highest hill; 2) similar deposits exist nearby on both the Climax-Scotts and Galesburg-Vicksburg outwash plains and in locations clearly not overridden by glacial ice subsequent to emplacement of the sands and gravels; 3) where the superposed units are exposed in a gravel pit, no evidence of glacial overriding was observed; 4) even where relatively thick, the upper unit was never found to be calcareous; and 5) aside from exhibiting great enrichment with fines, the upper unit appears texturally similar to the one it overlies. Perhaps, as suggested by Shah (1971), the finer fraction was eluviated from surface deposits of either eolian or slackwater origin.

Large boulders are almost completely lacking on the moraine, though they are abundant in both the adjacent interlobate area and the streamlined plain. Cobbles are locally present, most notably in the northeastern portion of the feature and adjacent outwash plain, but they tend to be scarce or absent elsewhere. Pieces of coal were found in the sands and gravels throughout the moraine, and Red Jasper Conglomorate and Gowganda (?) Tillite were present in many of those areas on the moraine where cobbles exist. All of these circumstances suggest a Saginaw Lobe origin for the sediments.

Two especially noteworthy exposures are within the boundary of the moraine as mapped by Leverett (Leverett and Taylor, 1915; Leverett, 1924a), Martin (1955), and Farrand (1982): an American Aggregates pit and a smaller private operation located in the SW, Sec. 22, T. 2 S., R. 9 W. and SW, Sec. 5, T. 3 S., R. 9 W., respectively. The former is near the northwest margin of the Climax-Scotts Outwash Plain and reveals coarse sands and gravels, cobbles, and many large boulders. Most of these sediments were obviously deposited near an ice margin by swift-flowing water.[3] There is a gentle southward dip to the exposed strata. At the latter exposure cut-and-fill structures indicate desposition from the northeast. At both locations evidence from sedimentary structures and particle sizes imply a Saginaw Lobe origin for the drift.

Other interpretations of the moraine's extent (Shah, 1971; Monaghan and Larson, 1982) place one or both of the above sites just outside its margin. Thus the two exposures may not be relevant for inferring the provenance of drift associated with the moraine as they map the feature. Even if located outside its limits, however, these sites show that the surficial sands and gravels in the western portion of the Climax-Scotts Outwash Plain are related solely to the Saginaw Lobe. This is contrary to interpretations on the manuscript maps of Martin (undated).

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[3]At least 11 meters (35 feet) of outwash are exposed in the east wall of this pit. Mike Cisco, a civil engineer for the company, stated that drilling indicates the deposit may extend 21 meters (70 feet) or more deeper. This information and the presence of kettles in the outwash nearby that are up to 15 meters (50 feet) deep indicate considerable deposition. Perhaps the area lies over a bedrock or pre-last-advance valley. None is shown on the map of Forstat (1982) but the drift here is relatively thick (approximately 60 meters (200 feet)) and relatively few water wells penetrate to bedrock. Moreover, a nearby oriented lake chain similar to others described in Michigan by Rieck and Winters (1976) is also indicative of a pre-last-advance valley.

Topographic Characteristics

Stagnation Topography

A variety of distinctive ridges appears on aerial photographs of the moraine (Figure 23). These ridges are situated along the eastern margin of part of the feature; and, irrespective of the differing interpretations of previously cited workers, many or most are located within the borders of the moraine (Figure 24). Viewed monoscopically on large-scale panchromatic or color-infrared imagery, they are visible primarily because of tonal contrasts. They are most apparent on fallow fields or those with only a moderate crop cover. Mature corn obscures them as does the higher albedo associated with recently harvested areas. They are easily seen in stereo view.

Many of the ridges have convoluted or anastamosing patterns, but others are ovoid and some are nearly circular. A preferential northeast-southwest orientation is apparent for both the linear and ovoid forms. Relief on the features may be as great as 5 or 6 meters (20 feet) but commonly is less. The ovoid and circular forms generally are less than 50 meters (165 feet) in diameter and the ridges typically range from about 100 meters (328 feet) to nearly a kilometer (.6 mile) long.

These landforms become less distinct both to the north and east where they merge with flat areas associated with the Climax-Scotts Outwash Plain. The distal (east) border of the features is obscure in many places, but toward the west they are generally replaced by hummocky and knob and kettle topography. Relief, both on them and on the moraine as a whole, tends to increase westward.

Figure 23. Stagnant-ice landforms associated with the Tekonsha Moraine of the Lake Michigan Lobe. Photo designation: BDW-1HH-160, 9-1-67, scale 1:20,000.

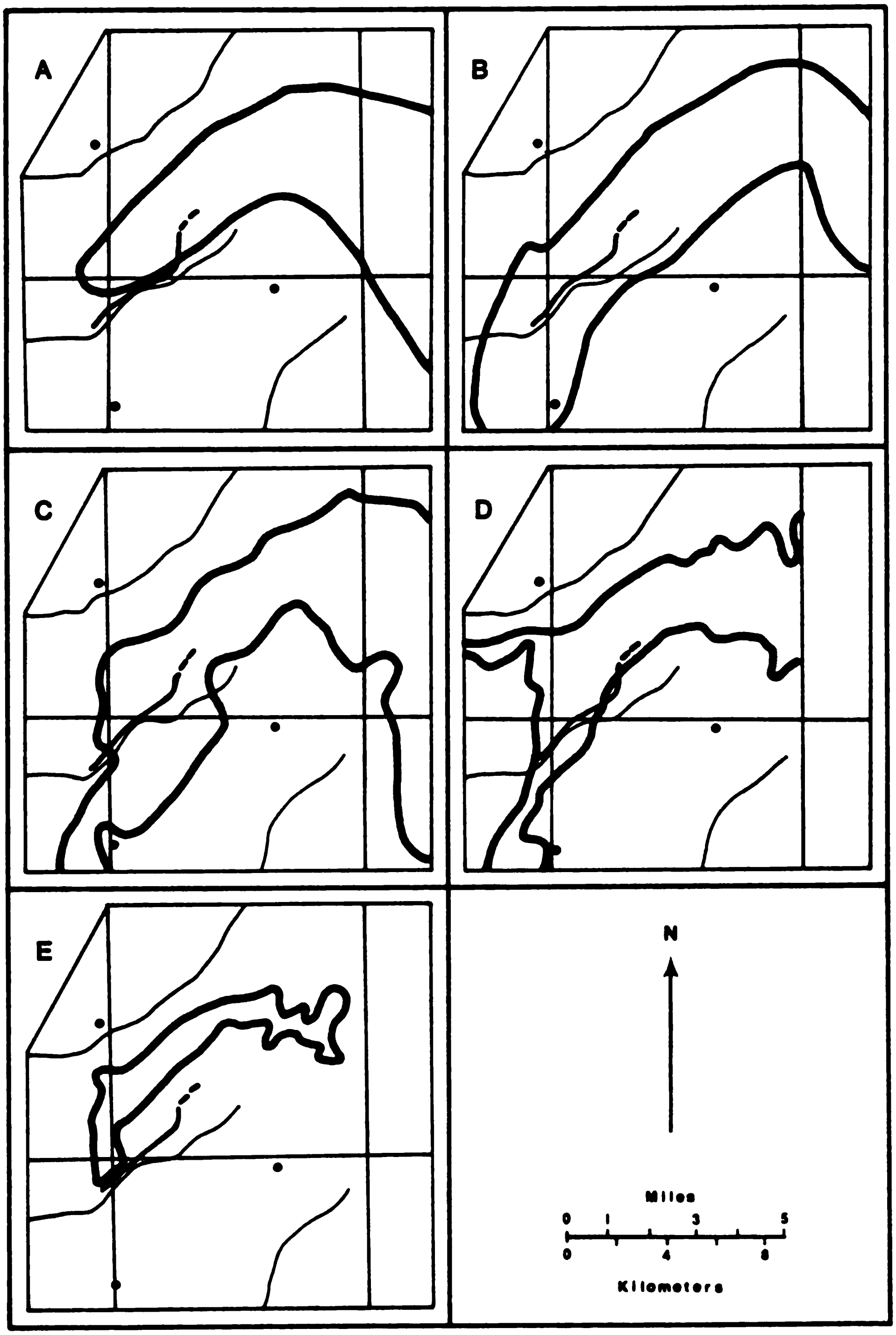

Figure 24. Various interpretations of the Tekonsha Moraine of the Lake Michigan Lobe. Leverett, 1915 (A); Leverett, 1924a (B); Martin, 1955 (C); Shah, 1971 (D); Monaghan and Larson, 1982 (E). The bold line on each diagram marks the distal limit of stagnation topography.

This assemblage of features indicates the former presence of a highly perforated and crevassed stagnant ice mass, most likely with detached ice blocks in some places, over which glaciofluvial sediments were deposited. Similar forms in Canada have been described in detail and interpreted in a like manner by Parizek (1969). The westward increase in relief here may reflect a greater thickness for remnants of the Lake Michigan Lobe in that direction.

Elevation Relationships

Koteff and Pessl (1981) have shown that topographic profiles along a zone rather than a line transect allow inferences about the original depositional surface for areas of ice-stagnation topography. Therefore, to more fully characterize the moraine, such profiles were constructed. Three transect orientations were utilized: along the approximate long axis of the feature, perpendicular to its western margin, and normal to the slope of the adjacent Climax-Scotts Outwash Plain (Figure 25).

For the longitudinal transect, maximum elevations on the moraine decrease southward from the interlobate zone (Figure 25). Those profiles perpendicular to the moraine reveal a general increase in elevation from west to east, a rise that continues into the bordering outwash plain directly to the east. If the isolated hill on profiles D and H and several small hills west and northwest of Scotts are disregarded, the previous statement is true for every location on the moraine. The third set of transects shows that virtually all of the feature is at the same level or lower than corresponding locations on the Climax-Scotts Outwash Plain. Moreover, the accordance of elevations between the

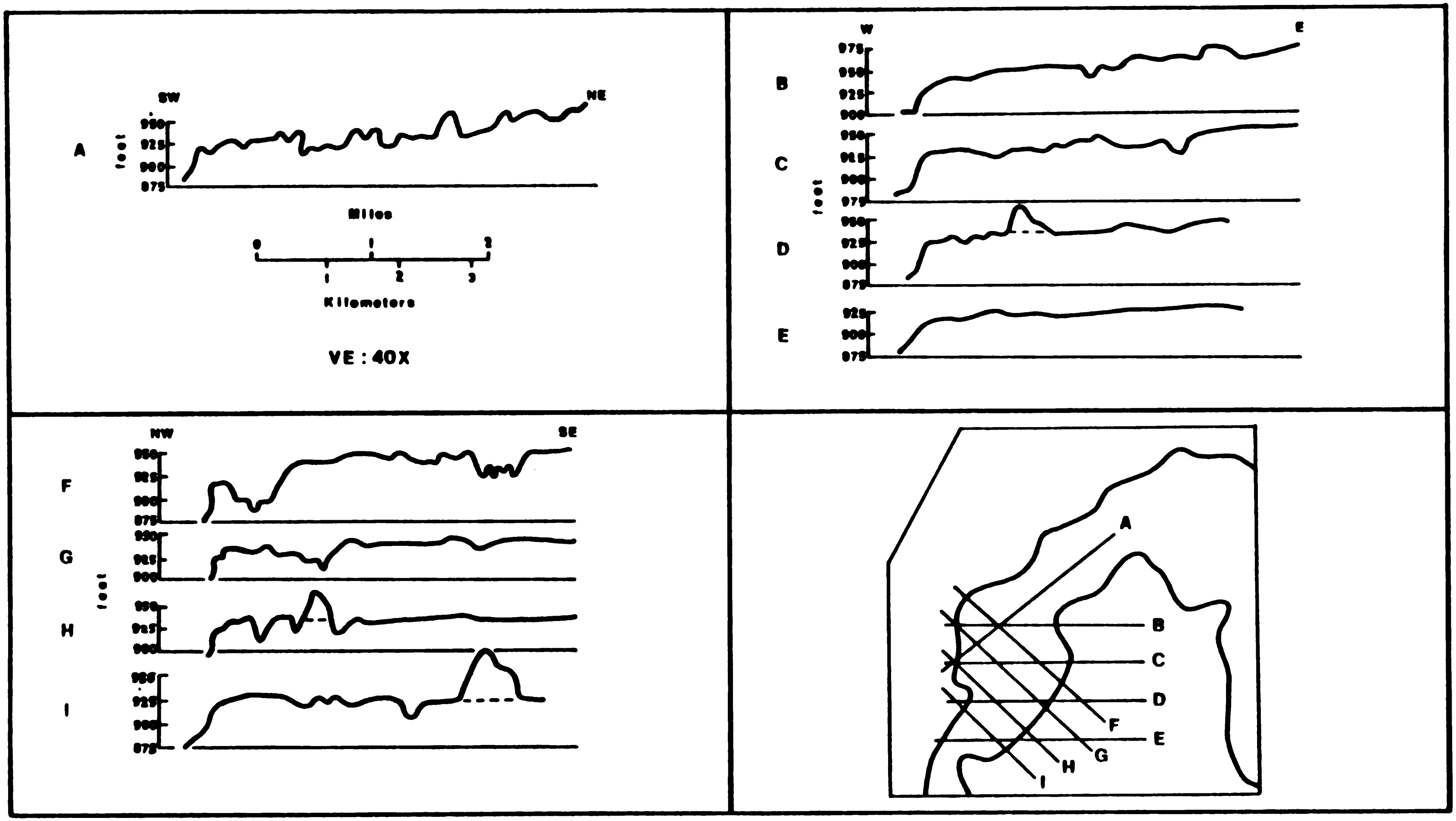

Figure 25. Topographic profiles across the Tekonsha Moraine of the Lake Michigan Lobe. See text for explanation.

highest areas on the moraine and the level of the outwash plain is striking.

Objectively drawn, generalized contours provide a more regional depiction of the topographic situation (Figure 26). They reveal that no elevation differences exist between the moraine and the Climax-Scotts Outwash Plain, irrespective of where the boundary separating them is drawn. They also show a southwestward-dipping slope for the surface of both features.

These characteristics have important implications regarding the genesis of the moraine. The moraine and western portion of the Climax-Scotts Outwash Plain should slope to the east, away from the ice, if the Lake Michigan Lobe were its source. Instead, the two features exhibit an accordance of elevations when viewed normal to the axis of the outwash plain. Moreover, the pattern of generalized contours indicates that the surficial sediments in both are graded to the same level and had a common origin associated with the Saginaw Lobe. Only at a few locations along the west-bounding bluffs of the moraine is there even the suggestion of a Lake Michigan Lobe influence. There a small number of knolls rise several meters above the immediately adjacent hills on the moraine, but they are still well below the general elevation of the feature.

Associated Streamlined Features

Examination of large-scale aerial photographs and topographic maps shows the presence of several elongated hills associated with the moraine. They are aligned northeast-southwest and, although surrounded and partially obscured by outwash, appear to be streamlined. At least

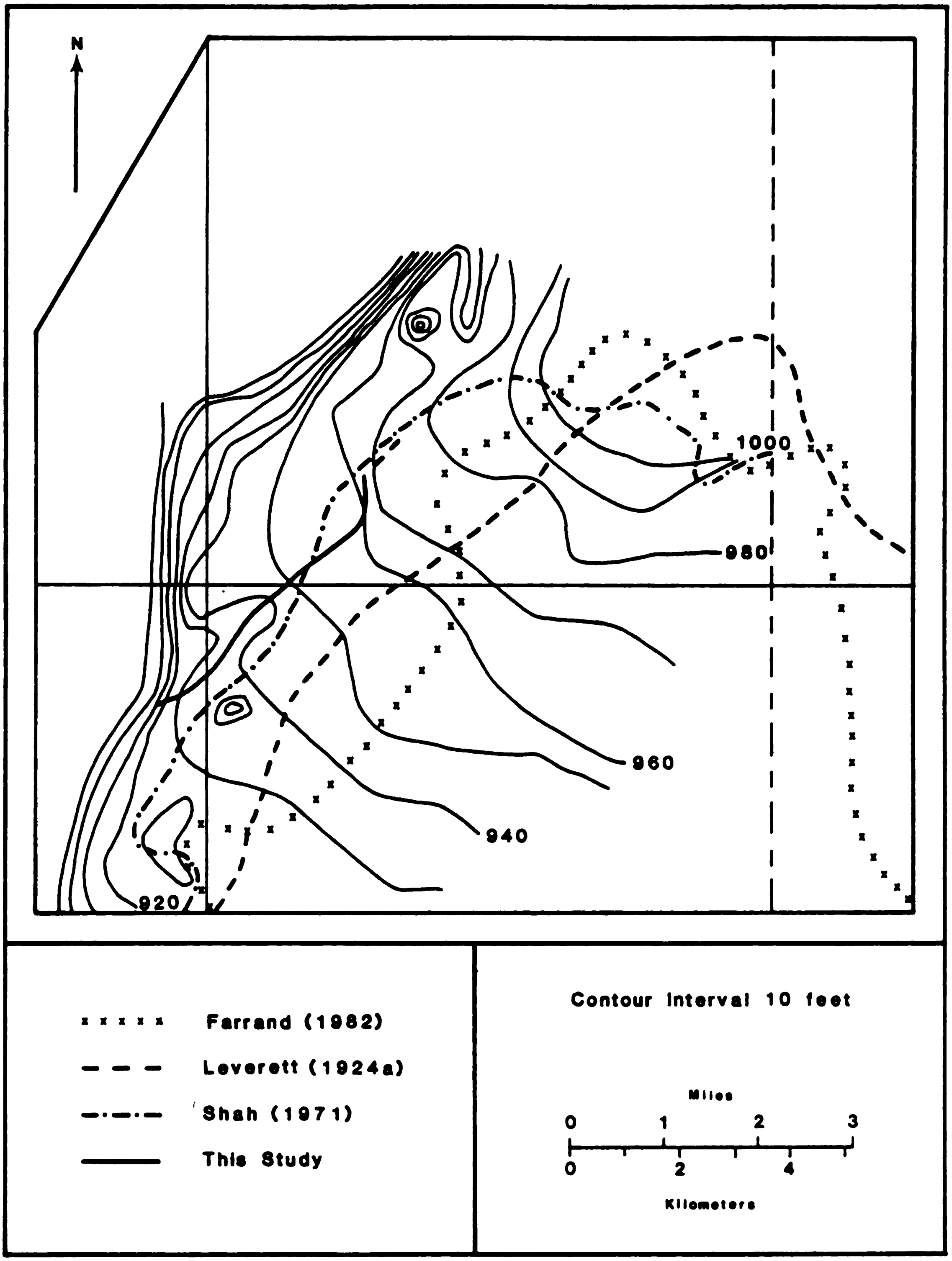

Figure 26. Generalized contours constructed across the Climax-Scotts Outwash Plain and the Tekonsha Moraine of the Lake Michigan Lobe.

four such features exist: one each in the SE Sec. 12, SW Sec. 13, NE Sec. 13, and NE Sec. 24, T. 3 S., R. 9 W. Aside from the hill depicted on the profiles (Figure 25), these are the only features even slightly higher than corresponding locations on the Climax-Scotts Outwash Plain. All four are within the moraine's boundaries as mapped by Leverett (1924a), Martin (1955), and Farrand (1982), but outside it as depicted by Monaghan and Larson (1982). Only the southernmost two are within the boundaries mapped by Shah (1971). All are distal to the border of stagnation landforms described below.

Till fabrics from the first two above-cited forms are aligned northeast-southwest, an orientation corresponding to both their elongation and that of the features on the Union Streamlined Plain just to the east (Figure 27). The 7/10A ratio for till from one of the hills, .82, is also similar to those for nearby drumlins and related forms. Based on these characteristics, the hills are interpreted as streamlined features produced by and composed of till from the Saginaw Lobe.

Till was also present at the base of a morainic hill in the center of Sec. 25, T. 2 S., R. 9 W., a site within the margins of the moraine as interpreted by all previous workers. The till fabric here was also oriented northeast-southwest and suggests Saginaw Lobe deposition (Figure 27). Moreover, this till was indistinguishable in the field from that in many of the nearby features on the streamlined plain. The 7/10A ratios for samples collected at the base and near the top of the hill were 1.17 and 1.24, respectively. These values are well within the range of other samples from features in the Union Streamlined Plain analyzed both by me and Monghan (1984). Possibly this site represents a completely "drowned" or overridden streamlined form. Irrespective of

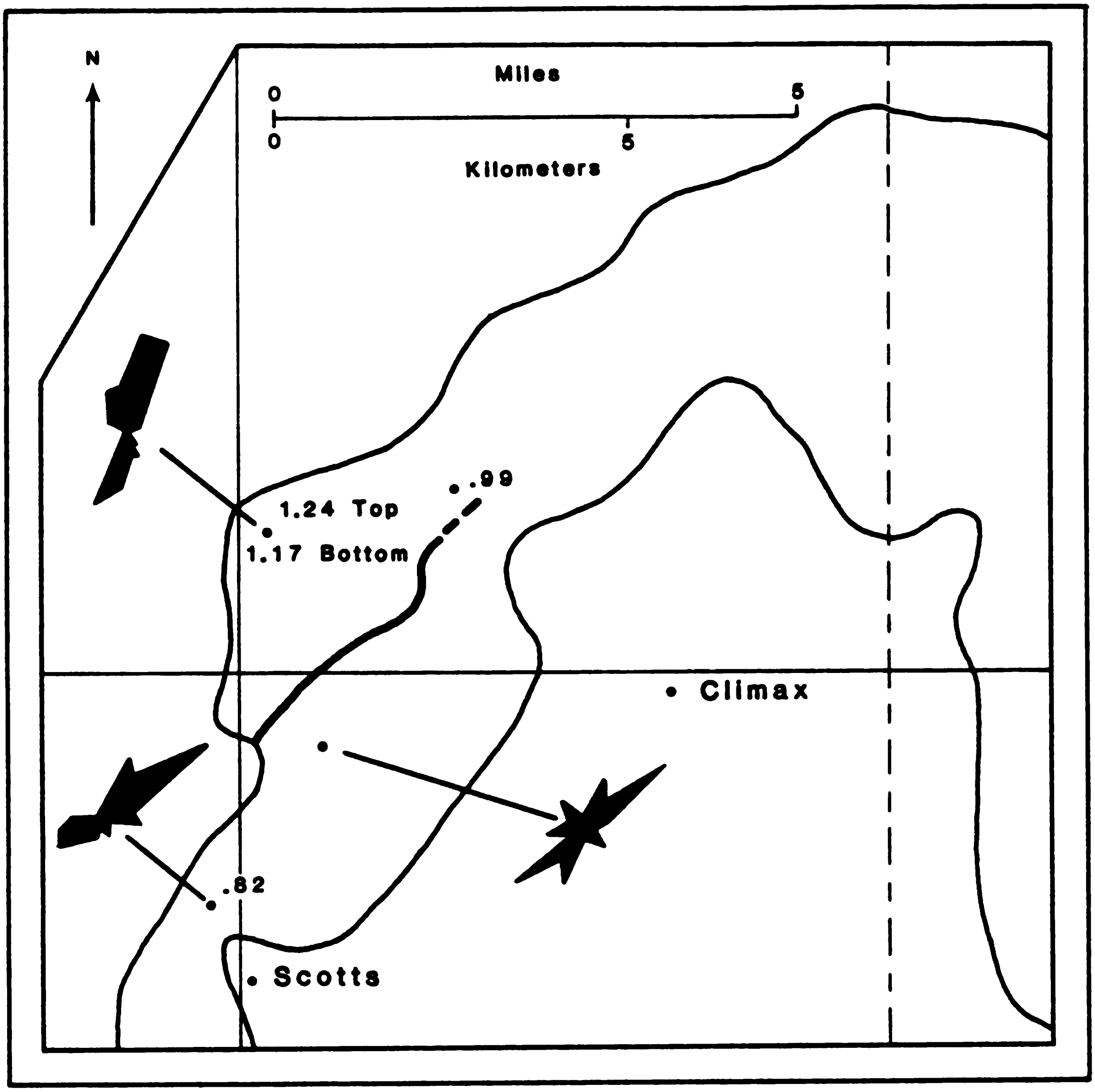

Figure 27. Till fabrics and 7/10A clay mineral ratios for sites associated with the Tekonsha Moraine of the Lake Michigan Lobe. The bold line marks the distal limit of stagnation topography discussed in the text.

that conjecture, however, all of the characteristics noted indicate a Saginaw Lobe origin for the till.

The sediment samples described above are interpreted as genetically related to and deposited at the same time as those of the Union Streamlined Plain. They, therefore, indicate a more westward extent for the Saginaw Lobe that the position of the Tekonsha margin of the Lake Michigan Lobe would otherwise suggest. Moreover, because drumlins and streamlined features form some distance behind an ice margin (Menzies 1978/1979), the westward, Woodfordian limit of Saginaw Lobe influence is uncertain. Perhaps it reached as far as the position of the Kalamazoo Moraine of the Lake Michigan Lobe in central Kalamazoo County. According to Straw (1976), and Erhart and Priced (1980), that location marks the approximate boundary between photolinears aligned with flow directions attributable to either the Saginaw or Lake Michigan lobes. Whatever its limit, however, a westward extension for the Saginaw Lobe has been hypothesized by others, including Leverett (1924b), Zumberge (1960), and Shah (1971). But, because neither they nor any other worker had recognized the streamlined forms associated with the moraine, their conclusions are based on different lines of evidence than those presented here.

Formation of the Moraine

With the exception of Dodson (1982) and herein, no published description of the moraine suggests that its manner of formation was in any way unusual. Shah (1971) specifically stated that it was a "push moraine." But the feature only partly conforms to the accepted definition of a moraine (Flint, 1971).

Based on the evidence presented here, the following deglaciation sequence is proposed. After formation of the Union Streamlined Plain and related features, the Saginaw Lobe ice front retreated to at least the position of the Tekonsha Moraine (if the withdrawal was greater, there was a subsequent readvance to that margin). Some time later the Lake Michigan Lobe advanced to a position at or near the eastern limit of stagnation topography shown in Figure 24. There it stagnated and was inundated by sands and gravels emanating largely, if not entirely, from the Saginaw Lobe. During this time a more active portion of the Lake Michigan Lobe held a position at or near the presently mapped western margin of the moraine and obstructed the drainage. Blockage does not seem to have been complete, however, as I have found no evidence for large-scale ponding. Instead, the meltwaters seem only to have been impeded sufficiently to deposit much of their sediment load. Part of the drainage probably flowed over, through, or under the ice dam, but some may not have reached it. In an unpublished manuscript Leverett (1918b) writes that the Lake Michigan Lobe blocked drainage from the Climax-Scotts Outwash Plain and diverted it down Little Portage Creek as well as along the ice margin in places. I concur with this assessment.

Melting back of the Lake Michigan Lobe ice front left the west-bounding bluffs of the moraine and the Climax-Scotts Outwash Plain rising well above the newly exposed area. At some time during this retreat meltwaters confined between ice of the Lake Michigan Lobe and the moraine probably eroded the bluffs somewhat, perhaps even to the extent of causing some eastward migration of their position.[4]

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[4]Erosion of the proximal bluffs was proposed by Leverett (1915, 1918b) and reiterated by Martin (1957).

Eventually, melting of the partially or fully buried ice finished formation of the present landscape. It exhibits morainic topography and marks a former ice margin, but it was not produced by direct glacial action. Instead, the landform is genetically a collapsed outwash plain more properly described as a significant ice-marginal position.

Tekonsha Moraine of the Huron-Erie Lobe

Previous Descriptions

Leverett (Leverett and Taylor, 1915) described the western margin of the Huron-Erie Lobe as marked by a poorly defined moraine forming an undulatory tract that trends generally southwestward from Quincy to just east of Orland (Figures 1, 28). His later mapping (Leverett, 1924a), although modifying the precise boundaries and location of the morainic segments, kept this general pattern. The interpretations of Martin (1955, 1957b, 1958) closely parallel Leverett's latter view. Zumberge, too, portrayed the area but with a major difference. He attributed the morainic tracts in central Branch County to the Saginaw, not Huron-Erie Lobe (Figure 28). The Huron-Erie border as mapped by Johnson and Keller (1972) bisects these tracts. Moreover, unlike previous accounts, they did not terminate the margin at Quincy but extended it about 15 kilometers (9 miles) to the east. The Huron-Erie margin as inferred from the map of Farrand (1982) can also be—and has been by Taylor (1984)—interpreted to extend east of Quincy. However, that distal border, as shown by them, is slightly south of the Huron-Erie margin as mapped by Johnson and Keller (Figure 28).

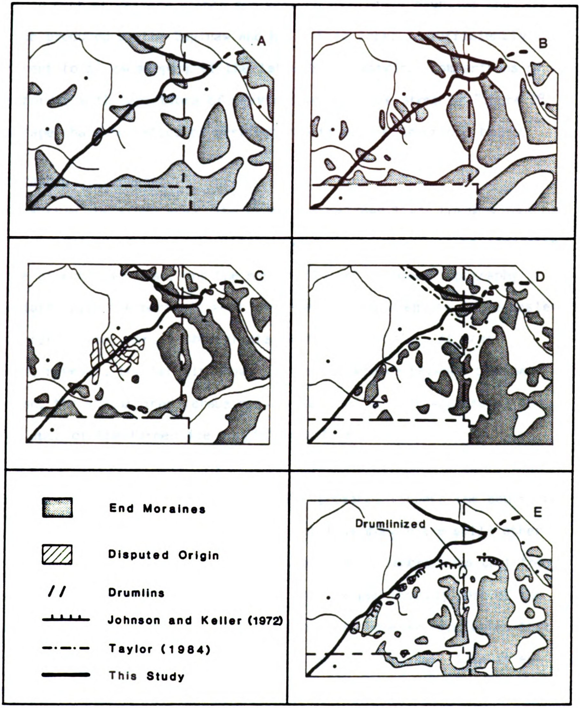

Figure 28. The Huron-Erie margin as interpreted by previous workers and herein. Leverett and Taylor, 1915, (A); Leverett, 1924a (B); Martin, 1955 (C); Farrand, 1982 (D); Johnson and Keller, 1972 (E). See text for explanation.

Reinterpretation of the Huron-Erie Margin

In much of eastern Branch and western Hillsdale counties the terrain produced by the Saginaw and Huron-Erie lobes is sufficiently different to allow mapping of the latter's ice margin. Comparisons of this border with depictions of previous workers are shown on Figure 28. Landscape characteristics of pertinent sections are described below.

Topographic Differences

Within the study area, the Union Streamlined Plain borders much of the Huron-Erie drift margin. Differences between the smoothed landscape of the streamlined tract and the more hilly and hummocky topography associated with the morainic area are generally apparent on large-scale topographic maps, aerial photographs, and in the field. At some places, however, the terrain shows little difference between the two. Even so, the streamlined versus non-streamlined terrain was useful to infer much of the former ice margin's position.

Well-developed drumlins exist in the northeast extension of the Union Streamlined Plain (Figure 20). But proximal (toward the south) to the associated portion of the former Huron-Erie margin are still other streamlined hills. Their alignment and proximity demonstrate that they, too, were produced by the Saginaw Lobe and are genetically part of the tract. Glacial modification of these features, however, indicates that they were subsequently overridden by the Huron-Erie Lobe. This is especially apparent along the Branch/Hillsdale county border at the survey line separating townships 5 and 6 south. To the north is a prominent drumlin lacking any indication of post-formation modification. To the south is a more subdued, apparently streamlined hill whose surface is covered by small morainic knolls. The difference between these two landforms is apparent both in the field and on large-scale aerial photographs.

The northern, and part of the western, drift margin of the Huron-Erie Lobe as here interpreted is based on the limit of that overriding. Of placements by others, this delineation most closely follows that of Johnson and keller (1972), apparently the only previous workers to recognize streamlined topography east of Quincy. Moreover, they also map drumlinized terrain proximal to the border of the Huron-Erie drift (Figure 28). Thus the different interpretations of drift boundaries arise neither from disagreements over the presence of streamlining nor about subsequent overriding of the features. Instead, Johnson and Keller must have viewed the overriding as less extensive than mapped here. A more thorough discussion of this follows later in the chapter.

About 8 kilometers (5 miles) south of Coldwater the streamlined terrain ends. But other landform characteristics permit boundary demarcation at some places to the south. For example, where the former ice margin crossed the present course of the Coldwater River, the valley is constricted. Because the river follows the trend of a buried bedrock valley here, the narrowing is apparently caused by drift deposited along the ice border that has not been removed by post-glacial valley-forming processes.

Farther south, especially near Sec. 18, T. 7 S., R. 6 W., the Huron-Erie landscape is characterized by a billowy topography. Although not rugged, it is quite different from the relatively flat adjacent terrain produced by the Saginaw Lobe. Also, several small kames are proximal to the former ice margin, for instance, in Sec. 24, T. 7 S., R.

7 W. Exposures in two of them reveal sand. In another close by, sand with interbedded flow till, cobbles, and small boulders is present. Additionally, there are two eskers or eskerine forms about 3 kilometers east of the former ice margin in Sec. 29, T. 6 S., R. 5 W. and Sec. 4, T. 7 S., R. 5 W. Thus, subdued morainic topography and some ice-stagnation landforms characterize the landscape just proximal to the Huron-Erie drift boundary. The absence of these features and the presence of the Union Streamlined Plain to the immediate west demonstrate that this drift border represents the maximum extent of the Huron-Erie Lobe during the late Woodfordian.

Outwash Plains and Associated Hydrography

As shown on the Kinderhood, Bronson South, Mongo, and Orland, 7.5' quadrangles, an apron of outwash slopes west and northwest away from the former margin of the Huron-Erie Lobe; the eastern extent of this outwash nicely delimits that position. In contrast to conditions at the source of the Climax-Scotts Outwash Plain, the material here is much finer textured, sand and gravel predominate, and relatively few large boulders are present. Apparently this is largely the result of lesser amounts of meltwater and a more tranquil depositional environment. Why there are fewer large boulders is, however, uncertain.

The outwash apron is on both sides of the earlier-formed Sturgis Moraine. Those sediments south of that feature may have been deposited on top of a Saginaw-Lobe-derived outwash plain. The present westward-inclined surface extends for approximately 10 kilometers (6 miles) along the front of the Sturgis Moraine. Beyond that is a southward-sloping outwash plain associated with the Sagainw Lobe. Presumably this latter deposit originally fronted the entire moraine and now lies beneath those sands and gravels from the Huron-Erie Lobe.

The spatial distribution of marshy areas and depressions also provides some indication of the southern portion of the former Huron-Erie Lobe border. Such poorly drained areas are not associated exclusively with one lobe but both are located predominantly within Huron-Erie terrain. To some degree, therefore, they furnish corroborating evidence for the ice margin mapped herein.

With the exception of the area near the Sturgis Moraine and those places associated with bedrock valleys, the depressions are most concentrated near and proximal to the former Huron-Erie margin. More importantly, because relatively few exist in the adjacent outwash apron, the sand and gravel do not appear to have been deposited on or around stagnant ice blocks. Thus the time between formation of the Sturgis Moraine and deposition of the glaciofluvial sediments was sufficient to allow virtually complete melting of Saginaw ice from the area. And the lack of Huron-Erie ice there is additional evidence that the border mapped herein marks the maximum extent of that lobe during final deglaciation of the region.[5]

Soils

As shown on the soil survey of Branch County (Moon and Wildermuth, 1928), the spatial distribution of two soils, Miami and Bellefontaine, is especially noteworthy. Without exception, Miami is mapped only within the limits of the Huron-Erie Lobe as here interpreted. Other

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[5]According to Farrand and Eschman (1974), this portion of Michigan was deglaciated approximately 15,000 years ago.

soils may tend to be associated with a single lobe but none have that exclusive relationship. The Bellefontaine Series is primarily along the ice-marginal positions of both the Saginaw and Huron-Erie lobes. But, disregarding those occurrences along the Saginaw border, the preponderance of land in Branch County covered by this soil is associated with the Huron-Erie margin. Thus this series, too, exhibits a distinctive lobal affinity.

A modern soil survey is presently nearing completion in Branch County; and, though still subject to revision, the entire county has now been re-mapped. One change is the subdivision of several established soil series and the recognition of new ones. As was true with the older survey, the distribution of two newly defined soils developed on till parent material, Hatmaker and Kidder, shows a notable lobal correspondence: Hatmaker with Huron-Erie Lobe deposits, Kidder with Saginaw Lobe sediments. Therefore, the spatial distribution of soils provides corroborating evidence for placement of the Huron-Erie margin as interpreted herein. And if, as seems most likely, the differences between these soils are a function of dissimilar parent materials, more specific characteristics of the sediments may reflect lobal provenance throughout this area.

Evidence for an Advance of the Huron-Erie Lobe Over Saginaw Deposits

Several authors have suggested or shown that in nearby regions of Indiana and Michigan ice of the Huron-Erie Lobe advanced over till deposited by the Saginaw Lobe (Mallott, 1922; Leverett, 1924b; Zumberge, 1960; Wayne and Zumberge, 1965). This overriding has never been demonstrated for the study area but the maps of some workers can be interpreted to infer it. Martin (1955, 1958) shows two drumlin symbols within morainic segments she assigns to the Huron-Erie Lobe. And as described above, Johnson and Keller (1972) map drumlinized topography proximal to their demarcation of the Huron-Erie margin (Figure 28). This study has identified still other topographic and sedimentary characteristics that support the interpretation of overriding.

Topographic Evidence

The presence of well-developed drumlins in the narrow, northeastern extension of the Union Streamlined Plain demonstrates that the Saginaw Lobe reached at least as far east as Allen. But the tract's southern margin here is well north that elsewhere. The result is a prominent bend to the southeastern border of the streamlined plain (Figure 20). If, as generally accepted, drumlins and related features form some distance behind an ice margin (Menzies, 1978/1979), how could the glacier conform to this outline and at the same time streamline landforms in the region? Necessary longitudinal flow patterns are difficult to imagine in a zone of drumlin forming, active ice with no topographic impediments to movement. Or, if ice of the Huron-Erie Lobe blocked the path and initiated localized shearing, how did the narrow band of drumlinized topography form on its northern margin? Surely this area would not be conducive to the production and preservation of such features. A reasonable assumption, therefore, is that, at least during the time it was actively forming the Union Streamlined Plain, the Saginaw Lobe covered and drumlinized part of the landscape proximal to the herein mapped Huron-Erie margin. This also indicates that ice of the latter lobe subsequently overrode deposits of the former. This sequence adequately explains the drumlinized topography proximal to the Huron-Erie margin mapped by Johnson and Keller (1972) and herein.

Till Fabrics

Fabrics collected from sites proximal to the Huron-Erie drift margin tend to exhibit two predominant orientations, northeast-southwest and northwest-southeast (Figure 29). Thus most seem referable to either the Saginaw or Huron-Erie lobes, respectively, and provide corroborating evidence that both lobes influenced this area. The two fabrics associated with streamlined hills that may have been overridden (sites 357 and 383) have a clear Saginaw alignment. Both topographic and till fabric data, therefore, support the interpretation of a more expansive Saginaw Lobe than bounding moraines otherwise indicate.

Several characteristics associated with a gently sloping morainic hill in Sec. 17, T. 7 S., R. 6 W. are especially notable. Till near the base of the hill has a change in color and texture at a depth of about 2.5 meters (5 feet). Because auger borings show that these color and texture changes are below the level of leaching, they cannot be pedogenic. Instead, they must reflect initial depositional conditions. Forming a boundary between the two units in places is a bluish-gray horizon of carbonate accumulation about a centimeter thick. The upper till is sandier and lighter brown compared to that below, but it is very similar to the till at the top of the hill and at other sites nearby. The more clayey and darker brown lower till contains many small pieces of coal. Although a small amount of coal is in the till above, it is not

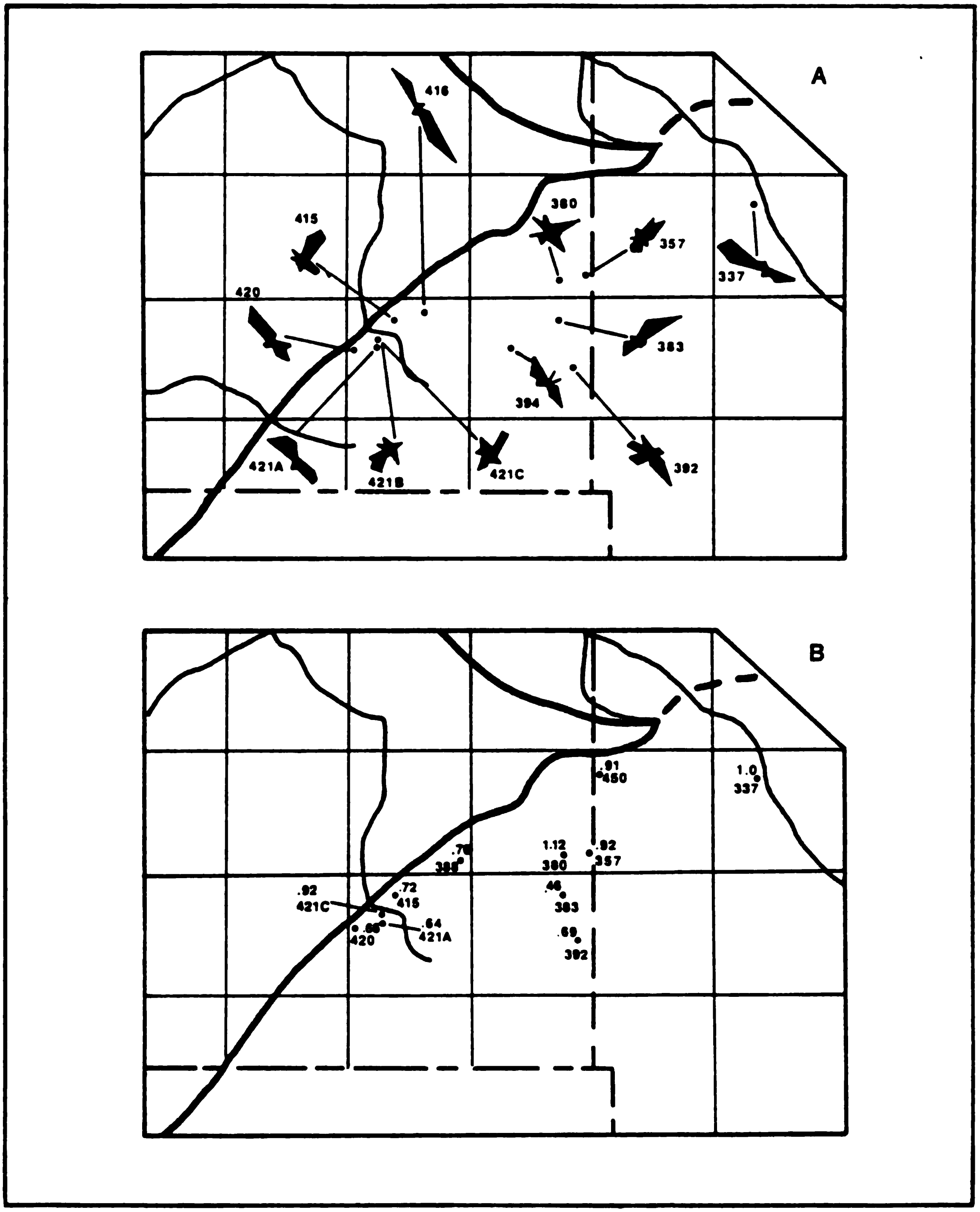

Figure 29. Till fabrics (A) and 7/10A ratios of clay minerals (B) for sites proximal to the Huron-Erie margin.

found in the till at the top of the hill or in the other similar tills nearby.

Three fabrics were determined from till in this morainic hill: one from its level crest (421A) and two from different depths but at the same place near its base (421B and 421C). Of the latter two, the top one (421B) was in the upper till and the lower one (421C) well below the color and texture boundary. The fabric from till at the top of the hill displays a pronounced northwest-southeast orientation similar to many others nearby and, like them, suggests Huron-Erie Lobe deposition (Figure 29). In contrast, that from the lowest unit (421C) is aligned northeast-southwest. It, therefore, indicates a Saginaw Lobe provenance, an interpretation further supported by the presence of the coal.

The fabric from the upper till unit near the base of the hill (421B) is also aligned northeast-southwest but may not record Saginaw Lobe flow. The alignment is in the same direction as the surface slope; and because the sampling surface was relatively shallow, 90 cm (36 in.), the fabric may have been reoriented by colluvial activity. But the preferred dip is upslope, not downslope, a condition difficult to explain by post-depositional movement of the surficial material. Perhaps the unit is an ablation or melt-out till and not indicative of ice flow. Whatever the cause of the orientation, several relationships at this site are especially important: 1) the matrix of the upper till unit (421B) is indistinguishable in the field from that on the level crest of the hill (421A); 2) the lower till unit (421C) is distinctly different from the other two associated with it; and 3) the fabric from the top of the hill (421A) and that from the base (421C) exhibit orientations referable to the Huron-Erie and Saginaw lobes, respectively.

The fabric from site 415, a morainic hill, also has a northeast-southwest orientation and may represent Saginaw Lobe deposition (Figure 29). Moreover, the sampling surface was below a thin horizon of carbonate accumulation similar to the one at the color and texture boundary described above. Possibly this site also has superposed till sheets. Whatever the genesis of this particular fabric, it is clear that stone orientations at some sites proximal to the Huron-Erie drift margin indicate Saginaw Lobe deposition.

Clay Minerals

Rieck (1976) and Rieck et al. (1979) have shown that the 7/10A ratio of clay minerals can be used to differentiate between tills of the Saginaw and Huron-Erie lobes near Jackson, Michigan. Because topographic characteristics and till fabric orientations show that superposed and adjacent deposits of these lobes exist in the study area proximal to the Huron-Erie margin, 7/10A ratios were examined to ascertain whether they can distinguish drift provenance here.

The 7/10A ratios typical of Huron-Erie Lobe till were characterized by those sites 1) located on non-streamlined morainic topography; 2) exhibiting a northwest-southeast aligned till fabric; and 3) where Red Jasper Conglomorate, Gowganda (?) Tillite, or abundant pieces of coal--all indicative of Saginaw Lobe sediments--are absent. Of the three sites meeting these criteria, 392, 420, 421A, all had ratios of less than .70 (Figure 29). The 7/10A ratios determined for nearby features in the Union Streamlined Plain were assumed to be representative of Saginaw Lobe sediments within the overridden area as well; those values were all greater than .76 (Figure 18). Therefore, distinction between these tills appears possible on this basis and a 7/10A ratio of .73 was used as a discriminator. In the study near Jackson, Rieck (1976) also found that the 7/10A ratios for Saginaw Lobe till are higher than for those associated with the Huron-Erie Lobe but there the discriminating ratio was .91, a substantially higher value than here.

Sediments from sites 357 and 388, both with topography that suggests prior streamlining and later overriding, have 7/10A ratios of .92 and .76, respectively (Figure 29). Till fabric at the former exhibits a northeast-southwest orientation. From these indications, therefore, both are Saginaw Lobe deposits.

Sites 380, 383, and 337 present conflicting evidence. The former exhibits a 7/10A ratio consistent with Saginaw Lobe deposition but is associated with a short ridge aligned just west of north and an indeterminate till fabric (Figure 29). Site 383, which topographically resembles a glacially overridden streamlined feature, has a Saginaw Lobe till fabric, yet the 7/10A ratio is .46, by far the lowest value for any site examined in this study. The reason for this is uncertain. Conversely, site 337 has a till fabric indicative of Huron-Erie deposition but a 7/10A ratio of 1.0, thereby suggesting it is composed of Saginaw Lobe till. Furthermore, Red Jasper Conglomorate and Gowganda (?) Tillite, both commonly associated with the Saginaw Lobe, were found at this site. Possibly this location represents Saginaw Lobe drift reworked by Huron-Erie ice.

Clay mineral data for the morainic hill with superposed tills is consistent with the other evidence. The 7/10A ratio for till from the top of the hill (421A) is .64, that for the lowest unit near the base of the hill (421C), .92 (Figure 29). Each, therefore, is clearly referable to deposits of a different lobe. Thus inferences based on clay mineral data and till fabrics, plus the presence of abundant pieces of coal in the lower unit, support the interpretation that this feature consists of till from the Saginaw Lobe that is mantled by deposits from the Huron-Erie Lobe. Site 415 may represent a similar situation but the .72 clay mineral ratio associated with it is considered ambiguous.

For several of the locations examined, inferences of lobal provenance based on 7/10A ratios are consistent with those derived from topographic or other sedimentary evidence. For some sites, however, there are disparate indications. These can be interpreted to suggest that the sedimentary measures are misleading and do not necessarily reflect lobal provenance here. But a more plausible explanation is that the advancing Huron-Erie Lobe incorporated varying amounts of the underlying Saginaw Lobe deposits. At different locations, therefore, the resultant till would contain a wide variety of the latter's components. For some sites dilution may be minimal, but at others it could be substantial. In this view, the data presented here are not an anomaly to be explained away. Rather, they are an expectable consequence of ice from one lobe overriding sediments deposited by another.

Formation of the Landscape

The topographic and sedimentologic evidence suggests the following glacial history. During formation of the Union Streamlined Plain active ice of the Saginaw Lobe extended at least as far east as Jonesville and for some unknown distance to the southwest. During this time it also drumlinized portions of the landscape that now lie proximal to the Huron-Erie margin. Subsequent to withdrawal of the Saginaw Lobe ice front, the Huron-Erie Lobe advanced to the position shown on Figure 28. For the study area, this marks the maximum extent of that lobe during the final deglaciation of the region. But contrary to the views of Leverett (Leverett and Taylor, 1915), Martin (1955, 1957B, 1958) and Taylor (1984) this ice-marginal position is not here interpreted as correlative with the Tekonsha Moraine of the Saginaw Lobe. Instead, the ice margin truncates and, therefore, post-dates that moraine.

CHAPTER V

SUMMARY AND CONCLUSIONS

The stated objectives of this dissertation are identified and discussed individually.

1. "Describe the morphology and measure certain morphometric properties of the streamlined landforms located within the Union Streamlined Plain."

   Topographically, the streamlined hills comprise a continuum of related features ranging from well-developed drumlins up to 14 meters (40 feet) high to rather indistinct elongated swells. Many of the hills have smooth crests not joined to any other streamlined form, but others are compound, consisting of more than one easily identifiable ridge. A large number, especially those in the southeastern portion of the tract, are arranged en echelon.

   Other related forms may be identified by remarkably straight, parallel, or near parallel lineations visible on aerial photographs of the region. These photolinears do not reveal positive topographic features but, instead, appear to represent a slight "scratching" of the landscape. Both the streamlined hills and lower areas apparent from the photolinears have similar orientations for any given area but exhibit a splaying pattern across the tract.

   In the southeast portion of the Union Streamlined Plain virtually all of the till landscape is smoothed and streamlined, the forms tend to be subdued, and photolinear density is high. To the west, however, the streamlined hills commonly are more prominent and clearly separable from those nearby, photolinear density is lower, and streamlined and non-streamlined topography is juxtaposed at many locations. Thus, two assemblages of landforms are present though their mutual boundary is amorphous. Notable spatial patterns also exist for several of the morphometric parameters. In particular, both feature elongation and photolinear density are greatest within the central zones of the tract. And, excluding the northeastern-most sub-region, height of the features tends to decline both toward the southwest and from west to east.

There are notable statistical correlations between several of the landform characteristics. Those with probable genetic importance are the negative correlations between photolinear density and feature height and the relationship of till texture to both k-value and stoss/lee ratio. For the former, increased photolinear density and lower feature height seem related to increased erosion. For the latter, tills with an increasingly coarse matrix apparently undergo greater resistance to deformation. This results in features with a more streamlined shape--less elongate and more asymmetrical. The phenomenon of thixotropy may also be important.

Both erosion and deposition contributed to formation of the drumlinized features in the Union Streamlined Plain. But in the southeastern portion of the tract, the concentration of photolinears, the lower hills, and the field evidence suggest that erosion was more important there than elsewhere.

The streamlining and deglaciation processes may also have been different for opposite sides of the tract. The areal distribution of juxtaposed and superposed non-streamlined topography —virtually absent in the eastern portion of the plain, widespread elsewhere--indicates that the ice within the region incorporated or transported different amounts of debris.

2. "Determine the spatial distribution and relationship to the bedrock surface of selected characteristics of the glacial sediments comprising the streamlined features."

Within the Union Streamlined Plain, many lithologic characteristics of the till matrix are directly related to elevation and lithology of the bedrock surface. At many places within the Marshall Cuesta, Coldwater Shale is at or near the surface and is a notable component of the superjacent till. Distal to that cuesta, however, that rock unit has lower elevations and a thicker drift cover, and its incorporation into the surficial drift is minimal or nonexistent. The boundary separating this change in till characteristics is remarkably abrupt and largely coincident with the trend of the drift-buried crest of the Marshall Cuesta. Similarly, within a short distance down-ice from the bedrock surface contact of the Marshall Sandstone and Coldwater Shale, the matrix of the surficial till exhibits substantial incorporation of shale.

For the surficial till, leaching depths, along with percentages of sand, silt, clay, calcite, dolomite, and total carbonates, also show marked areal differences. Each of them can be divided into two regions, one of higher and one of lower values, the boundary of which is similar or identical to the others. Moreover, for most of their length the borders closely follow either the trend of the drift-buried Marshall Cuesta or the bedrock-surface contact between the Coldwater Shale and the Marshall Sandstone. These characteristics represent a distinctive facies variation within the same till sheet, not the deposits of two glacial lobes. This demonstrates that composition of till can be strongly influenced by local bedrock conditions, a characteristic that should be carefully considered in any interpretations of glacial history.

Of the till properties examined, only two, calcite/dolomite and 7/10A ratios of clay minerals, were minimally or not noticeably affected by local bedrock conditions. If similar circumstances exist elsewhere, these ratios, or perhaps ratios in general, may be best suited to characterize rock-stratigraphic units in those areas where the local bedrock constitutes a substantial portion of the till matrix. Finally, because much of the Coldwater Shale was deposited within a short distance from its source, its erosion by direct glacial action appears unlikely. Instead, removal was accomplished largely by deformation of that part of the drift mass below the base of the ice.

3. "Describe the adjacent morainic areas and investigate their relationship to the streamlined forms."

Between its eastern and western portions, the Tekonsha Moraine of the Saginaw Lobe exhibits a marked change in drift composition. Toward the east, till and large boulders are common, but farther west, sand and gravel predominate. Differences in the terrain are associated with this sedimentary dissimilarity. Kettles, eskerine forms, and substantial amounts of outwash are present in the west but are either lacking or much less common in the east. This implies a different mode of deglaciation for the two regions; ice stagnation may have been widespread in the west but was of minor importance in the east. In fact, part of the terrain in the western portion actually marks an ice-marginal position rather than a moraine.

Along much of its length, the Tekonsha margin mapped herein is similar or identical to that interpreted by previous workers. But differences are marked in its easternmost section. Here, well-developed drumlins are present immediately distal to the border and show that the most appropriate boundary is north or east of placements by others.

In addition to the features within the Union Streamlined Plain, streamlined hills exist proximal to this Tekonsha margin. They are interpreted as genetically part of the tract and do not record a separate drumlinizing advance. Their orientation is the same as forms in corresponding portions of the streamlined plain, many are quite prominent and properly termed drumlins, and they are all composed mainly of till. Several have sand and gravel deposits high on their flanks or have substantial non-streamlined accumulations of till superposed on them. Both clay mineral data and till fabrics show differences between till from these streamlined and non-streamlined components of the landscape.

Much, if not all, of the Lake Michigan Lobe's Tekonsha Moraine north of Scotts, Michigan is composed of sands and gravels. Little to no till is exposed at the surface, large boulders are virtually absent, and cobbles are present only locally. Coal, Red Jasper Conglomorate, and Gowganda (?) Tillite are found in these surficial glaciofluvial sediments, suggesting a Saginaw Lobe origin for the deposits. Cut-and-fill structures at a gravel pit also indicate water movement from the northeast, but it should be noted that this site is outside the border of the moraine as defined by some workers.

Distinctive ridges with linear, anastomosing, ovoid, and nearly circular patterns appear on aerial photographs of the morainal tract. These patterns and features indicate the former presence of a highly perforated and crevassed stagnant ice mass, most likely with detached ice blocks in places, over which the glaciofluvial sediments were deposited.

Topographic profiles and generalized contours show that the border between the moraine and the east-bounding Climax-Scotts outwash Plain is an arbitrary designation if elevation is the only criterion. Corresponding locations for high places on the two landforms are at the same level. Moreover, these data also indicate that the Saginaw Lobe is the source of surficial sediments for both features.

The Tekonsha Moraine of the Lake Michigan Lobe exhibits rugged topography in places and marks a former ice margin, but it was not produced by direct glacial action. Technically, therefore, it is not a moraine. Instead, it is genetically a collapsed outwash plain. Moreover, the feature is unusual, if not unique, because the ice from one lobe was inundated by sediments emanating from another glacial lobe.

Several streamlined hills are associated with the Lake Michigan Lobe's Tekonsha Moraine though they are not necessarily within its borders as delineated by all previous workers. Each is elongated northeast-southwest; and, of those examined, all have similarly aligned till fabrics and contain till which is indistinguishable in the field from that in nearby drumlins of the Union Streamlined Plain. These forms are genetically part of the streamlined tract and demonstrate a more westward expansion of the Saginaw Lobe than the position of the moraine would otherwise indicate.

The Tekonsha Moraine of the Huron-Erie Lobe is poorly defined along much of its course within the study area. Where adjacent to the Union Streamlined Plain, however, its distal margin generally is sufficiently distinctive to allow delineation on large-scale topographic maps, aerial photographs, and in the field. Farther south other landform differences, especially the presence of small kames, billowy topography, and "heads of outwash," permit boundary demarcation, though with somewhat less confidence. Here, however, the areal distribution of soils and topographic depressions furnish corroborating evidence for its placement.

Streamlined topography formed by the Saginaw Lobe exists proximal to the Huron-Erie margin and demonstrates that ice of the latter lobe advanced over deposits of the former. Lobal provenance for sediments at a number of sites within the overridden area were determined with a combination of topographic and sedimentary criteria. Till fabrics tend to exhibit one of two predominant orientations, northeast-southwest or northwest-southeast. Thus most were clearly referable to either the Saginaw or Huron-Erie lobes, respectively. Fabrics from a morainic hill with superposed tills were especially revealing. The lower till exists near the surface at the base of the hill and had a Saginaw Lobe orientation. The fabric from the upper till exposed at the top of the hill exhibited a Huron-Erie alignment. These two units were also separable based on color and textural characteristics.

Clay mineral data also proved helpful in determining lobal provenance of sediments. The 7/10A ratios for streamlined hills associated with adjacent portions of the Union Streamlined Plain were all above .76. Those for sites proximal to the Huron-Erie margin and which also had northwest-southeast-aligned till fabrics, morainic topography, and a lack of Saginaw Lobe indicator stones were all below .70. Accordingly, a value of .73 was deemed appropriate to distinguish between deposits of the two lobes. Based on this criterion, most of the locations examined clearly represented one lobe or the other. But several sites were ambiguous; either the fabric or clay mineral data were indeterminate, or each indicated a difference provenance. These findings, however, are not interpreted to suggest that the sedimentary measures are erroneous. Instead, they are viewed as an expectable consequence from ice of one lobe overriding and partially incorporating sediments deposited by another.

4. "Interpret the deglaciation history of the study area."

During or following formation of the Sturgis Moraine, the Saginaw Lobe produced the Union Streamlined Plain as well as the drumlins and related hills in the surrounding morainic areas. Thus, for the study area, that component of ice flow fed by this lobe was laterally more extensive than present bounding moraines would otherwise indicate. This also suggests that the Saginaw Lobe was more powerful than generally recognized.

Subsequently, the Saginaw margin retreated to at least, and possibly beyond, the distal border of the Tekonsha Moraine. If the latter, the ice later readvanced to that location. Following this withdrawal, the Lake Michigan Lobe advanced to or near the eastward limit of stagnation topography shown on Figure 24. Here its outer portion became stagnant and was inundated by glaciofluvial sediments emanating largely if not entirely from the Saginaw Lobe. At this time the edge of the Saginaw Lobe was at a position marked by the Tekonsha Moraine; thus the two margins are time-correlative. Later retreat of the Lake Michigan Lobe ice front left the sand and gravel deposits well above the newly exposed terrain. The ice-contact, west-facing bluffs probably were eroded somewhat by meltwaters flowing between them and the Lake Michigan Lobe. Subsequent melting of the partially or fully buried inactive ice produced the stagnation topography.

The Tekonsha Moraines of the Saginaw and Huron-Erie lobes are not time-correlative. The latter lobe advanced over terrain previously occupied by the former but reached the location shown in Figure 28 only after the margin of the Saginaw Lobe had withdrawn from its Tekonsha position. This interpretation is indicated by the cross-cutting relationship of these ice margins and the absence of a reentrant feature similar to the Climax-Scotts Outwash Plain. Overriding was such that the drumlins and streamlined hills previously formed by the Saginaw Lobe were not completely obliterated. Final deglaciation of the study area left the landscape much as it is visible today.

Suggestions for Further Research

Results of this study suggest that additional research and analysis are warranted in the study area. This additional investigation seems justified because some of the findings are 1) opposite theoretical expectations, 2) somewhat subjectively derived, or 3) based on limited data, some for areas outside the study boundary. Moreover, it is not known whether certain of the statistical correlations and general conclusions are in agreement with conditions at other sites with similar relationships. The following are recommendations for further investigation.

Within the Union Streamlined Plain, correlations between measures of till texture and two landform parameters--elongation and asymmetry--were found to be statistically significant and compatible with theoretical conjectures. But the sample size is small. More importantly, if this association truly has genetic importance, similar interrelationships should be observable elsewhere. I hypothesize that statistically significant correlations between measures of till texture and values for elongation and asymmetry will be present in other drumlinized areas. To test this hypothesis, I recommend the investigation of at least two additional streamlined tracts. And to insure an adequate data base, landforms selected for these analyses should represent a range of till textures and topographic characteristics, should be part of a sample of more than 30 streamlined hills, and should be compared on an intratract, not intertract, basis.

Many till characteristics in the streamlined tract—depth of leaching and percentages of sand, silt, clay, calcite, dolomite, and total carbonates—have a notable spatial distribution and apparent relationship to the bedrock surface. The geographic distribution of each of these parameters can be divided areally so that the border separating the region of high values from that of low values is remarkably similar to the others and generally follows the drift-buried crest of the Marshall Cuesta. Although the delineation of these boundaries was not difficult, it, nonetheless, was subjectively accomplished, and this regionalization may have added credence if determined objectively. I suggest that the use of an objective procedure, such as cluster analysis, to group and areally subdivide the various till characteristics will produce results which replicate the spatial associations identified herein.

Unlike the pattern of most of the sedimentological properties examined, the areal distribution of 7/10A ratios was not distinctive. Nonetheless, statistical correlations indicate that incorporation of

Coldwater Shale probably influenced the clay mineralogy of till in the southeast portion of the Union Streamlined Plain. But characteristics of this shale were inferred from samples obtained outside the study area and reported elsewhere (Chung, 1973; Rieck, 1976). Because properties of the bedrock conceivably can change substantially over moderate distances, any further analysis of the relationship between shale entrainment and clay minerals should utilize data that are locally derived. If meaningful correlations are still present, they would constitute stronger evidence that incorporation of subjacent bedrock measurably affected the clay mineralogy of the overlying till. I suggest that the reported statistical correlations between 7/10A ratios and amount of Coldwater Shale incorporation (indicated by percent silt of the till matrix) be tested against values obtained from shale samples collected within the study area.

Leaching depths within the streamlined plain have several notable characteristics; among them, they are the greatest in the west, least in the east, and strongly correlated with measures of till texture. These findings, however, raise at least two questions: 1) does the regional pattern extend beyond the study area? and 2) does till texture remain highly correlated with leaching differences in other landscapes? The surrounding counties could be investigated to determine the former, but places both nearby and relatively distant need examination to resolve the latter. I hypothesize that till texture will be highly correlated with leaching depths in a variety of terrains. To facilitate comparisons with this study and to minimize possibly confounding factors, I recommend that future investigations utilize the field procedures adopted herein. In particular, only those level sites high in the landscape which appear to be composed of a single till unit should be sampled.

It is shown in the appendix that percentages of dolomite and total carbonates are positively and significantly correlated with leaching depths in the southeast portion of the streamlined plain. This relationship is contrary to theoretical expectations and not interpreted as causal. No significant association between these parameters exists for the area of deeper leaching. Because carbonates are known to be reprecipitated in a zone below the level to which leaching has progressed, Wenner, Holowaychuck, and Schafer (1961) recommend that samples characterising initial carbonate content be collected at least 76 cm (30 in) below the solum. Their procedure was followed in this study. Perhaps some factor associated with the relatively clayey tills on the southeast portion of the tract led to an increased thickness for the zone of reprecipitation here. If so, then this might explain the anomalous correlations; it was not initial carbonate content which was being measured.

I suggest that the positive correlations between leaching depths and carbonate content of the till resulted from a too shallow sampling depth. If this suggestion is correct, I would expect the zone of marked carbonate reprecipitation to extend more than 76 cm (30 in) below the base of the solum in the area of shallow leaching. But I would also expect that sampling depth to generally be adequate in the area with deeper leaching because the anomalous correlations are not present there. To test this relationship, several sites from both areas should be examined. At each location samples for carbonate content should be collected approximately 25 cm (10 in) apart starting at the level of initial effervescence and continuing down for at least 152 cm (60 in). Graphs of the resulting data will show how deeply marked reprecipitation extends.

APPENDIX

APPENDIX

Investigation of Leaching Differences

Introduction

It was demonstrated in Chapter III that a number of properties characterizing the till in the Union Streamlined Plain exhibit a similar spatial pattern. In particular, the shallow leaching depths in the southeastern portion of the tract are associated with finer-textured tills and lower carbonate contents, the greater depths elsewhere with coarser textures and more carbonates. The relationships between observed variations in the depth of leaching and three of the factors possibly responsible for those differences are presented in this appendix.

Factors Influencing Leaching Depths

Carbonate dissolution and reprecipitation is discussed by Birkeland (1974) and shown by the formula:

$$\begin{array}{c} CO_2 + H_2O \\ \upharpoonleft\downharpoonright \\ CaCO_3 + H_2CO_3 \rightleftharpoons Ca + 2HCO_3 \end{array}$$

But the complex mechanism controlling the amount of carbonate leaching in a given sediment involves a number of factors. Among those authors who have summarized possible causal relationships are Leighton and MacClintock (1930), Flint (1949), MacClintock (1954), Merritt and Muller (1959), and Ingmar and Moreborg (1976). These may be grouped under the following headings: time, permeability, original carbonate content, climate, depth to the water table, vegetation, topographic situation, stratification of parent material, and erosion and deposition downslope.

Time

For humid regions with other factors being equal, the longer the time available, the greater the depth of leaching. Differentiation or correlation of drift units based on depth of leaching measurements utilizes this attribute (Thornbury, 1940; Dreimanis, 1957).

Permeability

Permeability is the rate at which water and air move through rock or soil (Strahler, 1971). Because relatively impermeable soils allow less water to pass through them than do more permeable ones, the former should experience lesser amounts of carbonate removal than the latter. Factors contributing to the percolation rate include the texture and porosity of the sediment and the presence or absence of soil pans (Ingmar and Moreborg, 1976).

Original Carbonate Content

Many authors, among them Merritt and Muller (1959), Acton and Fehrenbacher (1976), and Ingmar and Moreborg (1976), have reported a negative correlation between original carbonate content and the depth of leaching in till. Working with gravels, MacClintock (1954) found this relationship to be inconsistent though it should be noted that some of his conclusions are challenged by Denny (1956). The ratio between magnesium carbonate and calcium carbonate (dolomite vs. calcite) might also affect leaching; as dolomite increases relative to calcite, the rate of leaching could decrease (Dreimanis, 1957).

Climate

Both temperature and precipitation may be important factors affecting leaching. Increasing temperature generally speeds up chemical reactions, but since it also raises the pH (lessens the acidity) of the soil solution by decreasing the solubility of carbon dioxide, its effects may be partially offsetting (Ingmar and Moreborg, 1976). More precipitation increases the water available for percolation, but its character is important, too (Ingmar and Moreborg, 1976). For example, thunderstorms can result in more runoff and less infiltration than will less intense, steady rains. The length of time the ground remains frozen may also affect the amount of water entering the soil.

Depth to the Water Table

Little leaching commonly occurs below the water table, though this is not necessarily true in a region of flowing groundwater unsaturated with carbonates (Flint, 1949). Perhaps more important, lowlands at or near the water table generally leach more slowly than do higher areas (MacClintock, 1954).

Vegetation

The more acid the percolating water, the faster leaching can progress. Therefore, to the extent that vegetation can influence the pH of the soil water, particularly from respiration or the decomposition of organic matter, it has an influence on carbonate dissolution. Apart from this, large amounts of moisture can be removed from the soil by transpiration, thereby lessening that available for leaching (Ingmar and Moreborg, 1976).

Topographic Situation

Because of variations in runoff, the crest, slope, and base of a hill will experience differing amounts of infiltration and, therefore, leaching. More specifically, Flint (1949, p. 299) states that "the thickness of the leached zone becomes thinner with increase of the surface slope directly above." However, Acton and Fehrenbacher (1976) report increased depths of leaching as one descends from the summit to the base of a hill irrespective of the surface slope. And the data of Ingmar and Moreborg (1976) suggest that the lower part of slopes have particularly great leaching depths. Apparently, other factors can substantially modify the influence of topographic position.

Stratification of Parent Material

Superposed strata which exhibit differing textural characteristics may influence leaching depths (Merritt and Muller, 1959). For instance, a clayey horizon overlying a sandy one could inhibit infiltration through the upper layer and thereby reduce carbonate removal throughout the profile. The opposite situation, a sandy deposit on top of a clay one, facilitates percolation and, consequently, leaching in the upper horizon but retards it in the lower unit.

Erosion and Downslope Deposition

Erosion or downslope deposition of previously leached material may result in misleading leaching measurements. In the former case, sediments will be removed, thereby lessening the depth to free carbonates. In the latter case, they will be deposited, thereby increasing the measured depth.

Procedures

Field and laboratory procedures for collecting data are fully explained in Chapters I and III. Samples were collected 76 cm (30 inches) below the leaching depth at 30 sites, each located along the level crest of a streamlined hill consisting of a single till unit. These procedures and the relatively small size of the study area are believed to minimize the influence of six of the variables identified as contributing to differences in leaching, specifically, time, vegetation, climate, topographic situation, stratification of parent material, and erosion and downslope deposition. The first two, however, warrant additional explanation.

Because all of the streamlined features were formed by the same ice advance and since there is no evidence to suggest that the ice remained over any portion of the tract appreciably longer than another, leaching of the forms should have begun essentially contemporaneously. This would be true even if some of the landforms were erosional and others were depositional because both would have had their newly sculpted and unleached surfaces exposed to weathering at the same time.

Virtually the entire tract lies within, or on the margin, of the oak-hickory forest association (Braun, 1972). Because of the large differences in till texture, however, there probably was some species diversity. Nonetheless, since broadleaf trees apparently grew on most or all of the streamlined features, the leaf litter should have been similar for all of them. Therefore, the influence of vegetation is believed to be minimal.

The procedures employed during sample selection minimized or eliminated the influence of all but three factors identified as contributing to differences in leaching. These--permeability, original carbonate content, and depth to the water table--were investigated in this study, and actual or surrogate measures were used to characterize each.

Sand, silt, and clay percentages were used as measures of soil permeability. It is fully realized that till texture only contributes to, but does not determine, actual percolation rates; but, given the restrictions noted above, this is believed to be a fairly reliable and easily determined surrogate.

The original carbonate content of the till was represented by calcite, dolomite, and total carbonate percentages, and the calcite/dolomite ratio. To minimize the problem of carbonate precipitation, all of the samples were collected 76 cm (30 inches) or more below the level to which leaching had progressed (see Chapter I).

Substantial differences in the depth to the water table exist between the southeastern portion and the remainder of the Union Streamlined Plain. For the former, it is relatively high and, during spring especially, was often encountered at shallow depths when augering. Mottles in the solum were also noted at many of these sites. Neither situation was observed elsewhere in the tract. The areal distribution of soils mapped within the drumlinized plain (Moon and Wildermuth, 1928; Austin, 1979) and information on their characteristics (Schneider, Johnson, and Whiteside, 1967) confirm the field observations: the water table associated with soils developed on till parent material is at a shallower depth in the southeastern portion of the tract, deeper elsewhere.

But depth to the water table is a difficult measure to obtain and no site-specific value is available. Consequently, three possible surrogates were identified. For each site the height of the feature's crest above both the immediately adjacent land and the nearest perennial surface water (pond, stream, marsh, etc.) was measured from topographic maps, the two variables being designated HTF and HTW, respectively. Also, a ratio (D/H) was calculated by measuring the horizontal distance from each site to the nearest perennial water body and dividing that distance by the height of the feature above the water. Because 1) for effluent water bodies the surface water level represents the elevation of the water table at that location (Strahler, 1971), 2) the water table tends to be a subdued version of the landscape (Bloom, 1978), and 3) steep slopes are absent or rare on the streamlined hills, these three measures may be reasonable approximations of the relative differences between the average depth to the water table at each site.

The relationships between depths of leaching and the three possibly causal factors are shown graphically with scattergrams and statistically with both simple correlations and multiple regression analysis. The analysis was, however, not as straightforward as one might expect. A histogram of leaching depths clearly shows their distribution to be bi-modal (Figure 30). And, with the exception of one site, those modes correspond to the contiguous regions of leaching depths discussed in Chapter III (Figure 18). Furthermore, the areal correspondence between the regions for leaching depths and those for many of the other sedimentological parameters examined suggests that two populations are present in the data.

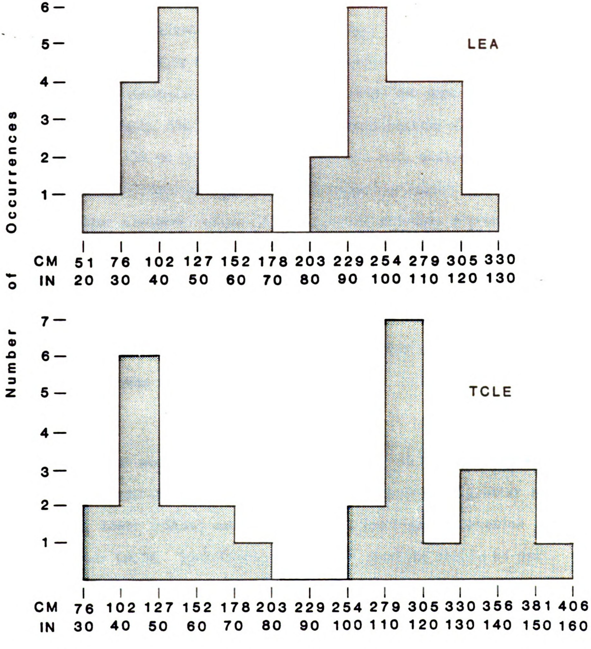

Figure 30. Histograms of leaching depths, both for field-measured (LEA) and carbonate-corrected (TCLE) depths of leaching and sand, silt, and clay percentages.

The statistical validity of the areal relationships was ascertained with a T-test which included all of the variables to be examined. The two groups tested were those sites with field measurements for leaching equal to or greater than, or less than, 178 cm (70 inches). The null hypothesis of no difference was rejected for all of the variables except calcite/dolomite ratios and show that two populations are present. Accordingly, the tract was divided into regions with less than and greater than 178 cm (70 inches) leaching and each analyzed separately. The former is identified as region X, the latter is region Y.

The proper placement of one anomalous site presents a problem. It is located within the shallow-leaching region and, therefore, appears to be a part of that population, but its 259 cm (102 inches) field-measured depth is clearly discrepant and suggests exclusion. For this study that site was considered to be part of the deeper-leaching group and the statistical analyses were conducted accordingly.

Hypotheses

Based on the above-discussed considerations, it is hypothesized that increased leaching will be associated with measures of greater soil permeability, lower initial carbonate content, and higher elevation above the water table. Specifically, depth of leaching should be positively correlated with sand percentage, and values for HTF and HTW; negatively correlated with clay, calcite, dolomite, and total carbonate percentages, and calcite/dolomite and D/H ratios.

Results

Till Texture

Scattergrams portraying the relationship between leaching and till texture show that increasing sand and decreasing silt and clay percentages are associated with greater depths of leaching (Figure 31). This is true irrespective of the leaching region examined (shallower, X, or deeper, Y) or the use of field-measured (LEA) or carbonate-corrected (TCLE) values.

Visual impressions from the scattergrams are substantiated by the quantitative analysis. For region X, leaching depths are positively correlated with sand percentages, negatively with those for silt and clay. The coefficients for sand and silt are statistically significant using either LEA or TCLE values, those for clay only with the latter (Table 7). In region Y, and for both measures of leaching, sand and clay percentages are significantly correlated with depths of leaching--positively for the former, negatively for the latter. Neither of the negative correlations with silt percentage attain significance, however (Table 8). Therefore, although the relationship with sand percentage is apparent in both regions, that of silt is pronounced only in one, that of clay primarily in the other.

In a comparison of the two regions, equal ranges of sand, silt, or clay percentages are not associated with equal differences in leaching. For example, a given increase in sand percentage corresponds with a much smaller change in the depth of leaching for region X than for region Y. Thus, the slope of the regression lines for sand, silt, and clay percentages is different in each region (Figure 31).

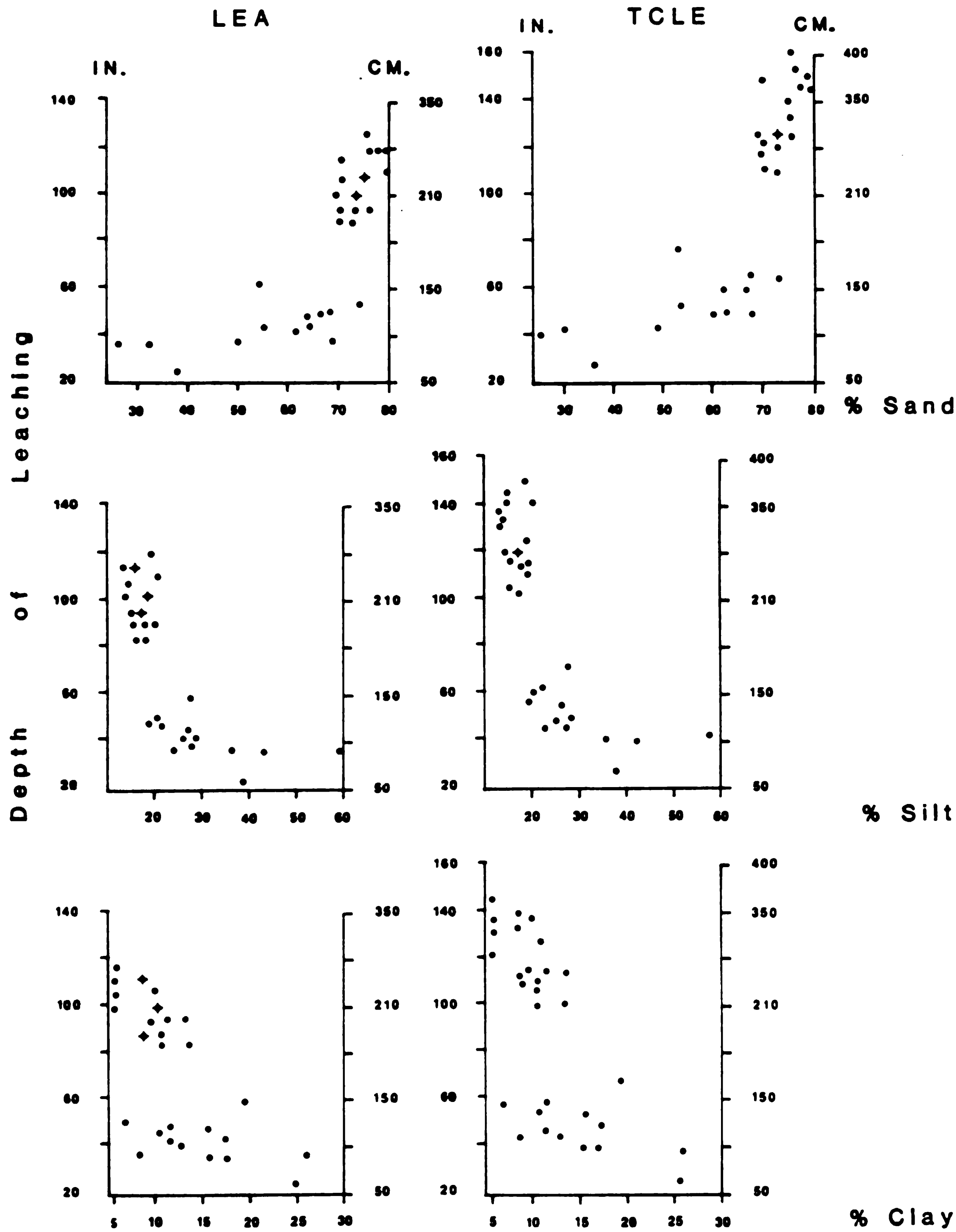

Figure 31. Scattergrams portraying relationships between field-measured (LEA) and carbonate-corrected (TCLE) depths of leaching and sand, silt, and clay percentages. + represents two sites.

	Sand	Silt	Clay	Calcite	Dolomite	Total Carbonates	Calcite/ Dolomite	HTF	HTW	D/H
LEA	.541 (.028)	-.540 (.028)	-.394 (.091)	.309 (.153)	.625 (.011)	.550 (.026)	-.259 (.196)	.471 (.052)	.009 (.489)	-.095 (.378)
TCLE	.618 (.012)	-.598 (.016)	-.485 (.046)	.467 (.054)	.751 (.002)	.689 (.005)	-.122 (.346)	.490 (.045)	-.010 (.487)	-.072 (.407)
Sand		-.947 (.001)	-.821 (.001)	.541 (.028)	.762 (.001)	.718 (.003)	.009 (.488)	.031 (.460)	-.189 (.268)	.322 (.142)
Silt			.594 (.016)	-.445 (.064)	-.639 (.009)	-.600 (.015)	-.011 (.486)	-.186 (.271)	.001 (.500)	-.218 (.237)
Clay				-.562 (.023)	-.772 (.001)	-.731 (.002)	-.004 (.495)	.252 (.203)	.472 (.052)	-.417 (.078)
Calcite					.883 (.001)	.937 (.001)	.708 (.003)	.323 (.141)	.016 (.479)	.005 (.493)
Dolomite						.991 (.001)	.332 (.134)	.302 (.158)	-.165 (.295)	.149 (.313)
Total Carbonates							.447 (.063)	.315 (.147)	-.118 (.351)	.122 (.358)
Calcite/ Dolomite								.160 (301)	.079 (.399)	-.231 (.224)
HTF									.691 (.004)	-.553 (.025)
HTW										-.494 (.043)

Table 7. Simple correlation coefficients (r) between depths of leaching and possible causal parameters for region X. Levels of significance are in parentheses, N=13. See text for explanation of abbreviations.

	Sand	Silt	Clay	Calcite	Dolomite	Total Carbonates	Calcite/ Dolomite	HTF	HTW	D/H
LEA	.541 (.013)	-.086 (.372)	-.627 (.004)	-.002 (.498)	.056 (.416)	.053 (.420)	-.005 (.492)	-.164 (.264)	-.157 (.273)	.161 (:268)
TCLE	.591 (.006)	-.143 (.293)	-.647 (.003)	.181 (.243)	.270 (.147)	.309 (.114)	.118 (.326)	-.080 (.381)	-.132 (.306)	:078 (:383)
Sand		-.630 (.003)	-.783 (.001)	-.301 (.453)	.462 (.031)	.335 (.094)	-.172 (.254)	.013 (.480)	.111 (.336)	-.120 (.323)
Silt			.010 (.484)	.099 (.353)	-.416 (.048)	-.252 (.165)	.323 (.185)	-.060 (.410)	-.269 (.149)	.334 (.095)
Clay				-.039 (.441)	-.262 (.155)	-.230 (.187)	.036 (.446)	.031 (.453)	.072 (.392)	-.112 (.334)
Calcite					.211 (.208)	.694 (.001)	.957 (.001)	.204 (.217)	-.052 (.421)	-.256 (.161)
Dolomite						.850 (.001)	-.079 (.382)	.211 (.208)	.093 (.361)	-.199 (.222)
Total Carbonates							.457 (.033)	.269 (.148)	.044 (.434)	-.287 (.132)
Calcite/ Dolomite								.154 (.277)	-.080 (.380)	-.198 (.223)
HTF									.883 (.001)	-.697 (.001)
HTW										-.680 (.001)

Table 8. Simple correlation coefficients (r) between depths of leaching and possible causal parameters for region Y. Levels of significance are in parentheses, N=17. See text for explanation of abbreviations.

Of the two regions, Y exhibits a substantially smaller range of sand, silt, and clay percentages; most of the till samples there, though not necessarily the soils, are sandy loams (USDA classification). To further assess the role of texture, correlations for those sandy loam sites were calculated and compared with the values from region Y as a whole. Coefficients from both samples are quite similar, although those from the sandy loam sites are slightly weaker. Nonetheless, the association of sand and clay percentages with depths of leaching remain statistically significant (Table 9). Thus, even within a single textural class, the relationship between till texture and leaching depths is pronounced.

Initial Carbonate Content

The scattergrams reveal that there is a tendency for increased leaching in region X to be associated with larger percentages of carbonates. However, for region Y, the plots appear amorphous and lack a readily identifiable relationship (Figure 32).

Correlations of depth of leaching with calcite, dolomite, and total carbonate percentages for region X are all positive, although only the latter two are statistically significant. It should be noted, however, that calcite nearly attains this when TCLE measures are used (Table 7). The strength of the correlations notwithstanding, perhaps the most important aspect of these relationships is their sign. Thus, increased amounts of carbonates are associated with greater depths of leaching, a situation opposite that hypothesized and contrary to all published accounts of leaching in till of which I am aware. Calcite/ dolomite ratios do not even approach statistical significance in region

	Sand	Silt	Clay	Calcite	Dolomite	Total Carbonates	Calcite/ Dolomite	HTF	HTW	D/H
LEA	.499 (.035)	.031 (.458)	-.572 (.016)	.139 (.318)	.008 (.489)	.125 (.336)	.141 (.316)	-.243 (.201)	-.238 (.207)	.289 (.158)
TCLE	.507 (.032)	.028 (.463)	-.578 (.015)	.280 (.166)	.124 (.336)	.301 (.148)	.262 (.183)	-.209 (.236)	-.247 (.197)	.252 (.193)
Sand		-.490 (.038)	-.685 (.003)	.089 (.381)	.244 (.200)	.232 (.212)	.022 (.471)	-.259 (.186)	-.078 (.396)	.186 (.262)
Silt			-.300 (.149)	.115 (.348)	-.212 (.233)	-.038 (.449)	.168 (.283)	.103 (.363)	-.176 (.273)	.197 (.250)
Clay				-.193 (.254)	-.090 (.380)	-.222 (.223)	-.164 (.283)	.197 (.250)	.232 (.212)	-.369 (.097)
Calcite					.077 (.397)	.794 (.001)	.983 (.001)	.196 (.251)	-.061 (.417)	-.303 (.146)
Dolomite						.666 (.005)	-.098 (.369)	-.107 (.358)	-.167 (.284)	.164 (.288)
Total Carbonates							.674 (.004)	.084 (.388)	-.146 (.310)	-.126 (.334)
Calcite/ Dolomite								.219 (.226)	-.035 (.453)	-.317 (.135)
HTF									.879 (.001)	-.659 (.005)
HTW										-.654 (.006)

Table 9. Simple correlation coefficients (r) between depths of leaching and possible causal parameters for sandy loam sites in region Y. Levels of significance are in parentheses, N=14. See text for explanation of abbreviations.

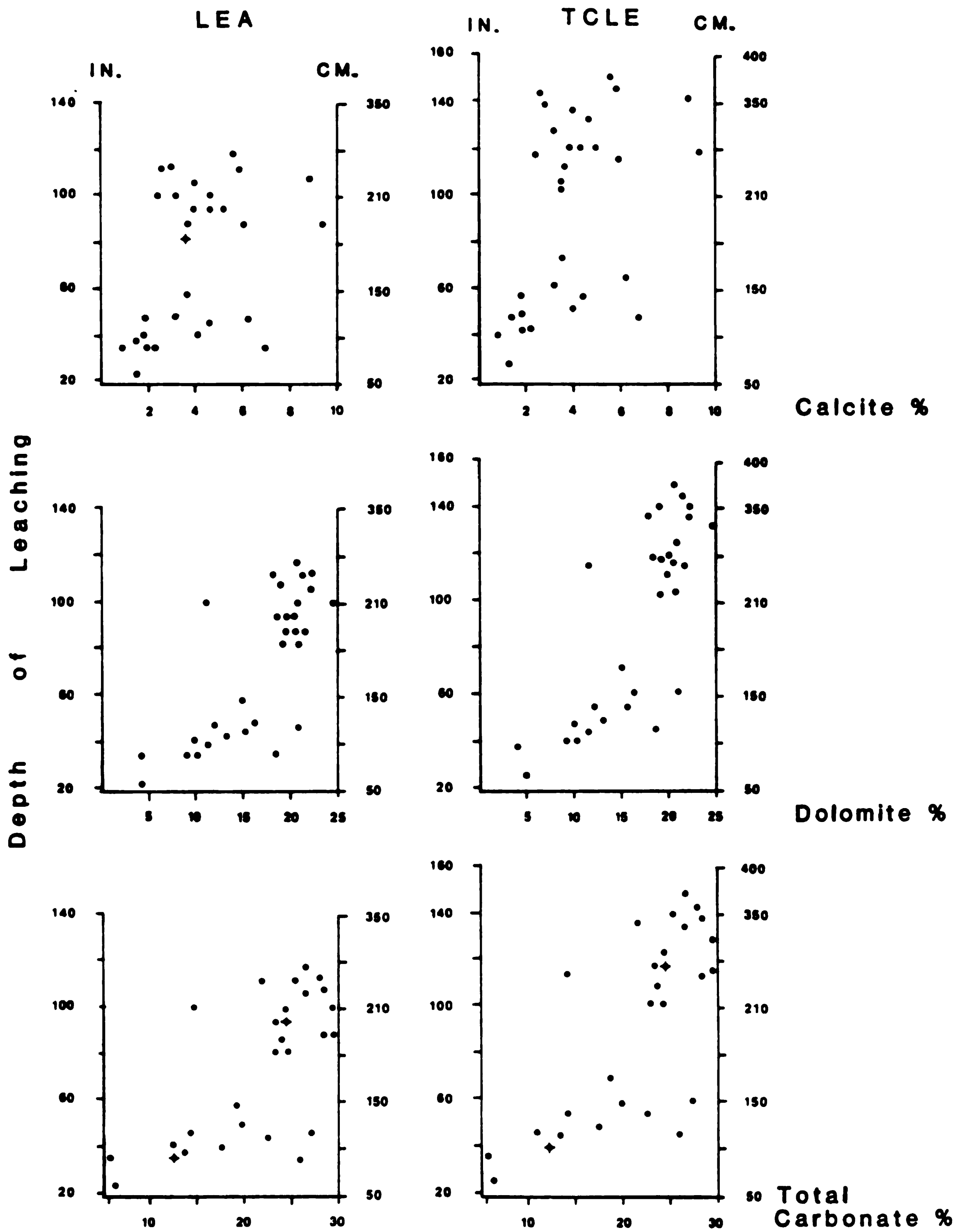

Figure 32. Scattergrams portraying relationships between field-measured (LEA) and carbonate-corrected (TCLE) depths of leaching and carbonate percentages. + represents two sites.

X, nor do any of the carbonate measures in the region of deeper leaching (Tables 7, 8).

Water Table Measures

Of the surrogate measures of the water table, only the relationship between HTF and leaching depths in region X is notable. Levels of significance for LEA and TCLE are nearly identical, .052 and .045 respectively, but given these values both might be better viewed as ambiguous. Nonetheless, there is a tendency for higher forms to exhibit greater depths of leaching than lower ones. None of the other measures even approach statistical significance in either region (Tables 7, 8). Visual impressions gained from the scattergrams indicate that the correlations adequately characterize the relationships (Figure 33).

Discussion

The statistical analyses show that, of the variables examined, till texture is the major factor associated with variations in the depth of leaching. This is true even for samples of the same textural class. Different constituents are important in the two regions, however. In the sandier tills of region Y, clay percentage exhibits the highest correlation with leaching. Conversely, its relationship is not statistically significant in the more clayey tills of region X, where sand and silt percentages are strongly correlated with leaching depths. Thus, though texture differences are always of consequence, the most important component appears dependent on the original composition of the till. These results are consistent with the original hypothesis, conform to generally accepted theoretical expectations, and are believed to represent causal interrelationships between the variables.

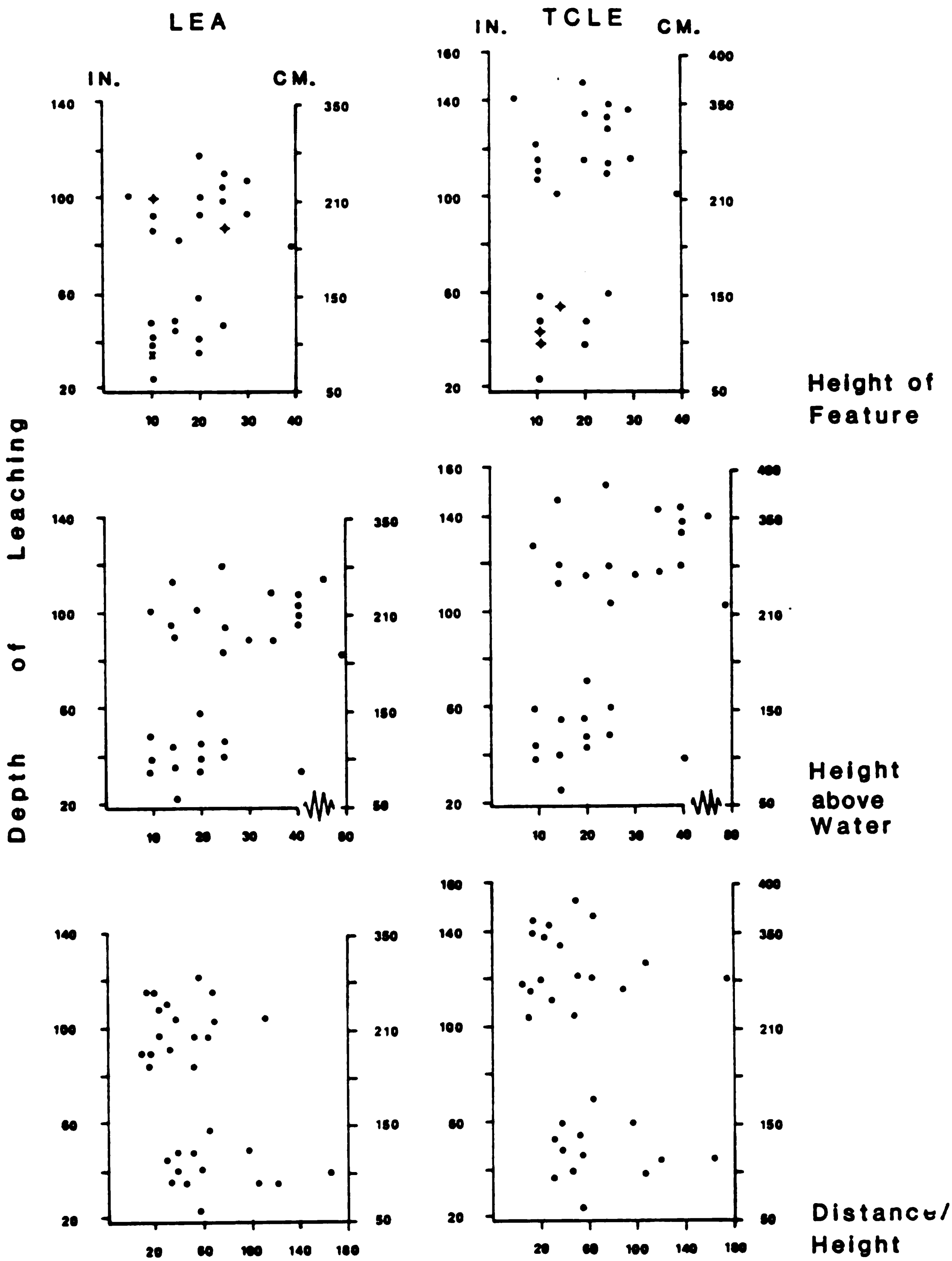

Figure 33. Scattergrams portraying relationships between field-measured (LEA) and carbonate-corrected (TCLE) depths of leaching and possible surrogate measures of the water table. + represents two sites.

The positive and statistically significant correlations between leaching and both dolomite and total carbonate percentages for region X are not believed to be causal. Other factors being equal, it is difficult to imagine a mechanism that would cause increased leaching simply because more carbonates were present. The possibility that these correlations are spurious was, therefore, examined.

In the region of shallower leaching, dolomite and total carbonate percentages are strongly and significantly correlated with all three components of till texture--calcite with sand and clay only (Table 7). It was demonstrated in Chapter III that this region is one of substantial incorporation of the non-calcareous Coldwater Shale bedrock. Increased amounts of that shale, therefore, lead to both finer-textured tills and to lower carbonate contents. And, since finer-textured tills have already been demonstrated to be associated with shallower leaching, the correlations between leaching and carbonates in this region might seem explainable as a function of the relationship between till texture and carbonates. But the results of a partial correlation analysis failed to support that supposition; mathematically controlling for the effects of till texture did not substantially reduce the correlations between leaching depths and carbonate amounts. This suggests that some other factor is operative.

Perhaps the sampling depth is too shallow and still within the zone of carbonate precipitation for these relatively clayey, less permeable tills. If so, it is not the original carbonate content that is being measured and the correlations are misleading. Moreover, it may also explain why the anomaly is confined to the shallow leaching area. In the region of deeper leaching the sampling depth presumably is adequate.

Perhaps, too, the differential solubility of calcite and dolomite is a factor. If the zone of precipitation for the former but not the latter extends below the sampling depth, it would explain why only dolomite and total carbonates (of which dolomite is the predominant component here) are positively and significantly correlated with leaching depths.

Aside from the ambiguous correlations between HTW and depth of leaching for region X, none of the surrogate measures of the water table displayed notable relationships with leaching differences. They are highly and significantly correlated with one another, however, suggesting an internal consistency of measurement (Tables 7, 8). Nonetheless, either these three indicators do not adequately characterize the water table, their influence is masked by other factors, or the water table exerts no substantial influence on leaching depths within each region.

To ascertain whether and how strongly multivariate relationships contributed to leaching differences, a multiple correlation and regression analysis was conducted for each region. Because the correlations between leaching depths and carbonate percentages in region X were not considered causal, sand percentage was entered into that equation first. In neither region did the analysis prove fruitful, however. Following the first iteration, none of the partial correlation coefficients attained statistical significance. This inability to demonstrate concomitant influences on leaching depths should not necessarily be interpreted as proof that such associations are lacking. If the correlations and trends evidenced for each region are generally accurate representations of relationships therein, a larger sample size may reveal those interrelationships.

The reason for the marked regionalization of leaching depths has not been determined. It does not appear to be simply a matter of differing till texture. If that were the case, regression lines on the scattergrams portraying sand, silt, and clay percentages versus depths of leaching for the two regions would be expected to exhibit a similar slope and Y intercept. Clearly they do not (Figure 31). Some other factor(s) must, therefore, modify the influence of till texture. Perhaps the areal differences in bedrock elevation and lithology, possibly through their effect on the water table, are somehow responsible for this as well.

Conclusions

Depth of leaching on similar landforms of the same age varies greatly within the Union Streamlined Plain. This is true irrespective of the use of field-measured or carbonate-corrected values. Sand, silt, and clay percentages are the variables most strongly and consistently related to these differences, a relationship that holds even when only sites of the same textural class are examined. Positive correlations exist between carbonate percentages and depths of leaching in the region of shallow leaching. They are not interpreted as reflecting a causal association, however. Instead, the sampling depth may be inappropriate. Surrogate measures of the depth to the water table did not exhibit significant correlations with leaching.

The results of this study demonstrate that utmost care should be taken when attempting to differentiate or correlate till units based on depth of leaching measurements. More than minimally dissimilar values for any of the possible causal variables, but for till texture in particular, could be associated with substantial leaching variations not attributable to temporal differences. Moreover, an adequate number of sites should be examined to reduce the possibility of sampling bias. These comments seem especially appropriate if one is attempting to delineate units of less than stage rank.

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