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The glacial geomorphology of the Port Huron Complex in northwestern southern Michigan

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THE GLACIAL GEOMORPHOLOGY OF THE PORT HURON COMPLEX IN NORTHWESTERN SOUTHERN MICHIGAN

By

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ABSTRACT

THE GLACIAL GEOMORPHOLOGY OF THE PORT HURON COMPLEX IN NORTHWESTERN SOUTHERN MICHIGAN

By

William Llewellyn Blewett

This study investigates the morphologic, sedimentologic, and chronologic aspects of Leverett and Taylor's (1915) Inner and Outer Port Huron Moraines in Kalkaska, Antrim, eastern Charlevoix and western Otsego Counties. Four principal landform units are recognized and include 1) the Outer Port Huron Complex, 2) the Inner Port Huron Complex (including the Mancelona Plain), 3) the Post Inner Port Huron zone, and 4) fluted uplands and through valleys.

Surficial sediments of the Inner and Outer Port Huron Complexes are almost exclusively 1) glaciofluvial sand and gravel, and 2) glaciolacustrine silt and clay. Till is almost wholly restricted to the fluted uplands and the Post Inner Port Huron zone. The Inner and Outer features each contain an uppermost wedge of sand and gravel up to 80 m thick, deposited on a moderate relief till surface inclined to the northwest. Crestal areas exhibit ice-contact and proglacial stratified drift and surficial boulders associated with deposition along marginally stagnant ice. Thus, proximal sediments are not "coarse textured glacial till" as mapped by others (Farrand and

Bell, 1982), but, instead are proximal facies of especially important heads of outwash.

Sediments related to the main surface of the Mancelona Plain (Elmira surface) show a transition from coarse, poorly sorted proximal deposits dominated by longitudinal bars to distal, fine textured, well-sorted braided stream deposits displaying sandy bedforms. Paleocurrent indicators show that meltwater streams first flowed perpendicularly away from the ice margin and then turned 90 degrees to the right to flow parallel to the sandur's axis.

The Mancelona Plain and Post Port Huron zone contain 10 and 16 separate outwash surfaces, respectively. Collectively, these surfaces record long intervals of quasi-stable ice-marginal conditions favoring thick outwash deposition, punctuated by brief transitional periods of rapid incision due to ice-marginal retreat. Landform and sediment relationships show that this retreat was characterized by an ice margin that pivoted clockwise to the northwest during final deglaciation.

The Inner and Outer Port Huron Complexes both display a distinct salient and reentrant pattern. Locations of the former are closely related to the magnitude of lower areas on the deeply buried bedrock surface. Both complexes 1) display alluvial fan-like profiles in cross-section, 2) exhibit prominent ice-contact slopes trending tens of kilometers in some areas, and 3) have hummocky proximal regions displaying hanging valleys, perched fans, and disintegration ridges. Combined with sedimentary evidence, these landform assemblages indicate that the terrain formed along successive marginally stagnant glacial terminii defined by at least nine morphosequences (Koteff and Pessl, 1981).

Finally, wood and other organic material associated with lacustrine silts located 50 m below the Mancelona Plain yield an age estimate of >41,000 yrs. B.P. Elsewhere, carbonaceous material from lacustrine deposits provides a minimum date of 12,960 $\pm$ 350 yrs. B.P. for the Port Huron Complexes, and, combined with age determinations from the Lake Border Moraine, indicates that the Inner and Outer Port Huron Complexes formed between 13,000 and 14,000 yrs. B.P. This estimate 1) agrees strongly with age estimates for correlatives of the Port Huron Moraine in Ohio and Ontario (Barendsen et al., 1957; Calkin, 1970), 2) helps verify correlation of the Port Huron Complex within Michigan (Leverett and Taylor, 1915), and 3), for the first time, provides a minimum date for the Port Huron Complexes in northwestern southern Michigan.

for Gretchen
and
for my family

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INTRODUCTION

Background

The Port Huron Morainic Complex marks one of the most conspicuous topographic complexes in southern Michigan (Leverett and Taylor, 1915, p. 293) and is interpreted as the outer limit of a significant glacial readvance c. 13,000 yrs. B.P. (Hough, 1958; Farrand and Eschman, 1974; Fullerton, 1980). First recognized by Taylor (1897, p. 41-43) in southeastern Michigan, the moraine was subsequently described in greater detail by Leverett and Taylor (1915) and, at the same time, extended north and westward nearly 550 km. Mapping was based primarily on morphology (Fig. 1). Leverett described the moraine in the northwestern part of the Southern Peninsula (Leverett and Taylor, 1915; p. 302-306) and recognized an inner and outer ridge separated by broad, relatively flat outwash surfaces he named the Mancelona Plain.

Although published more than 70 years ago, maps by Leverett and Taylor (mapping later slightly modified by Martin, 1955; and Farrand and Bell, 1982) remain the basic source for delineating glacial features in Michigan. Their use of the term "moraine" when describing the Port Huron feature follows accepted views

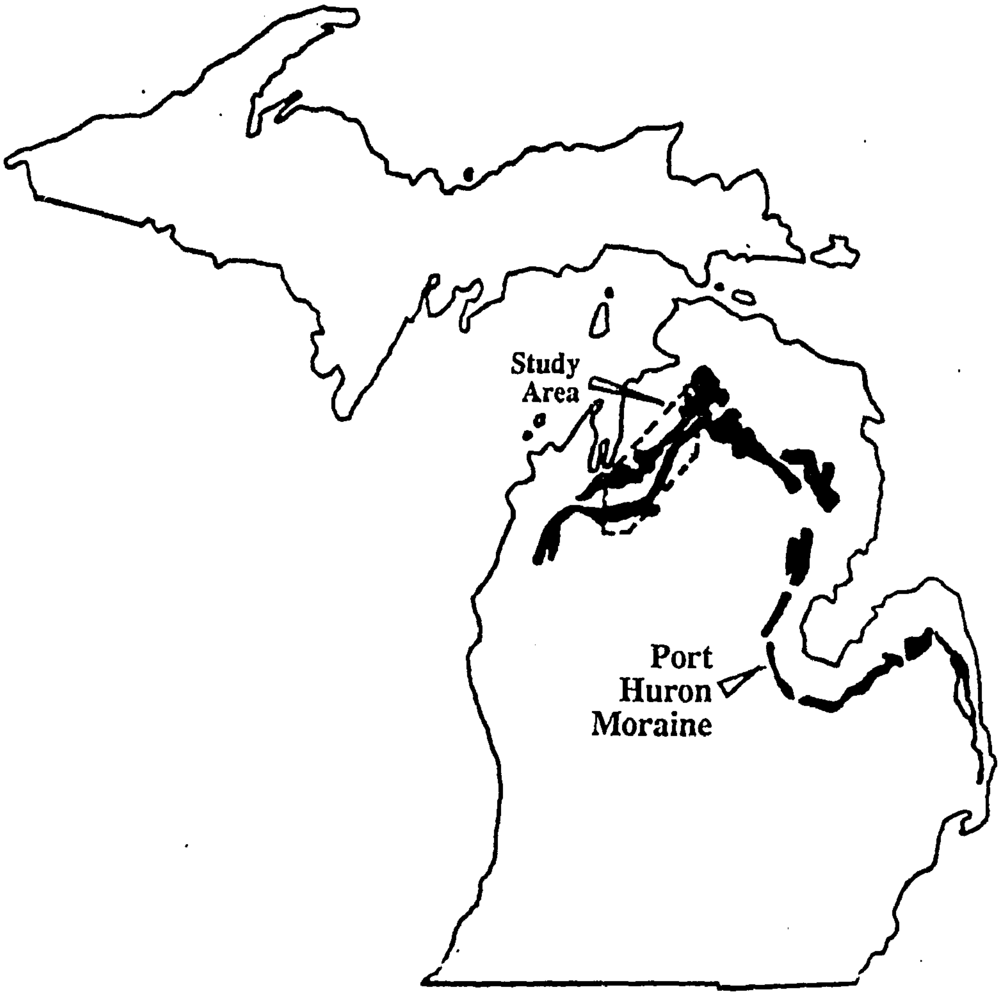

Figure 1. The Port Huron Moraine in southern Michigan
(after Leverett and Taylor, 1915).

of the time, which placed great emphasis on the importance of an active ice margin in producing the modern landscape. Martin's 1955 map perpetuated these ideas, as has Farrand and Bell's more recent mapping (1982). Certainly, Leverett and Taylor knew that glacial stagnation occurred within these morainic tracts. Data from newly available large scale topographic quadrangles along with detailed field mapping, however, indicate that stagnation was much more widespread during final deglaciation than previously recognized. In addition, water and petroleum well log data indicate strong positive relationships among drift thickness, bedrock topography, and modern terrain in some areas. Rieck and Winters (1979) documented similar relationships in southeastern Michigan but no such study has focused on the northwestern part of the Southern Peninsula. Thus, both data and increased understanding provide a basis and justification for reevaluating the Port Huron Complex in northwest-southern Michigan.

In addition, the Mancelona Plain has long been recognized as an especially important element in the interpretation of the complicated pattern of morainic remnants in this part of the state (Melhorn, 1954; Farrand and Eschman, 1974), but analysis of the feature has been limited. Topographic maps and aerial photographs clearly show that the Mancelona Plain is an assemblage of several outwash terraces trending parallel to the glacial margin, yet the relative age, significance, composition, and geographic distribution of these features remain unknown. Studies elsewhere (Fraser and Cobb, 1982) indicate that meltwater associated with similar outwash surfaces flowed both parallel and perpendicular to the glacial terminus, but no such study has addressed the Mancelona feature. Topographic maps and aerial photographs also show that numerous, previously undocumented, outwash surfaces exist proximal to the Inner Port Huron Complex.

Problem statement

This research concerns the nature and significance of landforms and sediments within Leverett and Taylor's Inner and Outer Port Huron Moraines, including the Mancelona Plain, in northwestern southern Michigan. The major questions addressed are:

1. What evidence exists for the presence of ice-contact and proglacial stratified sand and gravel, flow and ablation till, and other sediment indicative of stagnation?

2. To what extent does present topography display morphology typical of stagnant ice formation?

3. What evidence exists for the presence of several outwash surfaces within the Mancelona Plain?

4. What evidence exists for drainage both parallel and perpendicular to the ice margin on the Mancelona Plain?

5. What evidence exists for the presence of outwash surfaces proximal to the Inner Port Huron Complex?

6. To what extent does the bedrock surface influence modern topography?

7. What evidence exists indicating that this portion of the Port Huron Complex formed c. 13,000 yrs. B.P, as suggested in the literature (Fullerton, 1980)?

In addition to evaluating these questions, the study has two additional objectives of developing:

1. An improved physiography for the study area.

2. An interpretation of deglaciation, based on landform and sediment relationships.

Background and methods

Definitions and concepts - Early workers, following the prevailing views of the time, mapped many of the high-relief topographic trends in northwest-southern Michigan as "moraines." Flint (1971, p. 199) defined a moraine as "an accumulation of drift deposited chiefly by direct glacial action, and possessing initial constructional form independent of the floor beneath it." This implies that moraines are formed by active ice, and composed primarily of till.

In contrast, Koteff and Pessl (1981, p. 5) coined the term "morphosequence" and defined it as "a continuum of landforms composed of meltwater deposits, from more collapsed forms...to progressively less collapsed forms downstream. It can...be viewed as a body of stratifed drift laid down, layer upon layer, by meltwater at and beyond the margin of a glacier, while deposition was controlled by a specific baselevel." The morphosequence concept, which has proved useful in determining ice marginal positions where stagnation was predominant (Koteff, 1974), is applicable in the study area. Koteff

(1974, p. 121), who uses the term "morphologic sequence" in this early work, provides six criteria for designation of morphosequences:

1. Morphosequences predominantly consist of meltwater deposits including sand, gravel, silt, and clay. Till is usually absent except where it appears as flow till.

2. Morphosequences generally show a transition from more collapsed to less collapsed forms downstream.

3. Morphosequences are controlled by a specific base level, usually identifiable in the field.

4. Landforms making up a single morphosequence are considered to have formed at approximately the same time.

5. Sediments show a transition from coarse to fine texture downstream from the head of outwash.

6. Morphosequences can be distinguished using profiles drawn perpendicular to the head of outwash, and, where more than one morphosequence is present, express a shingle-like morphology.

The genesis of morphosequences and their associated landforms has been described in detail (Koteff, 1974; Koteff and Pessl, 1981) using the stagnation-zone retreat model of glaciation. This model assumes a thin stagnant zone at the ice margin with active ice immediately up-glacier. At the juncture between the two zones, shear planes develop, supplying basal sediments to a superglacial location in the stagnant zone (Fig. 2). Meltwater and mass wasting transport these sediments beyond the ice margin, forming outwash aprons or deltas depending on the proglacial environment. Sediments associated with these two features exhibit a facies change from coarse to fine distally, with boulders deposited near the ice margin.

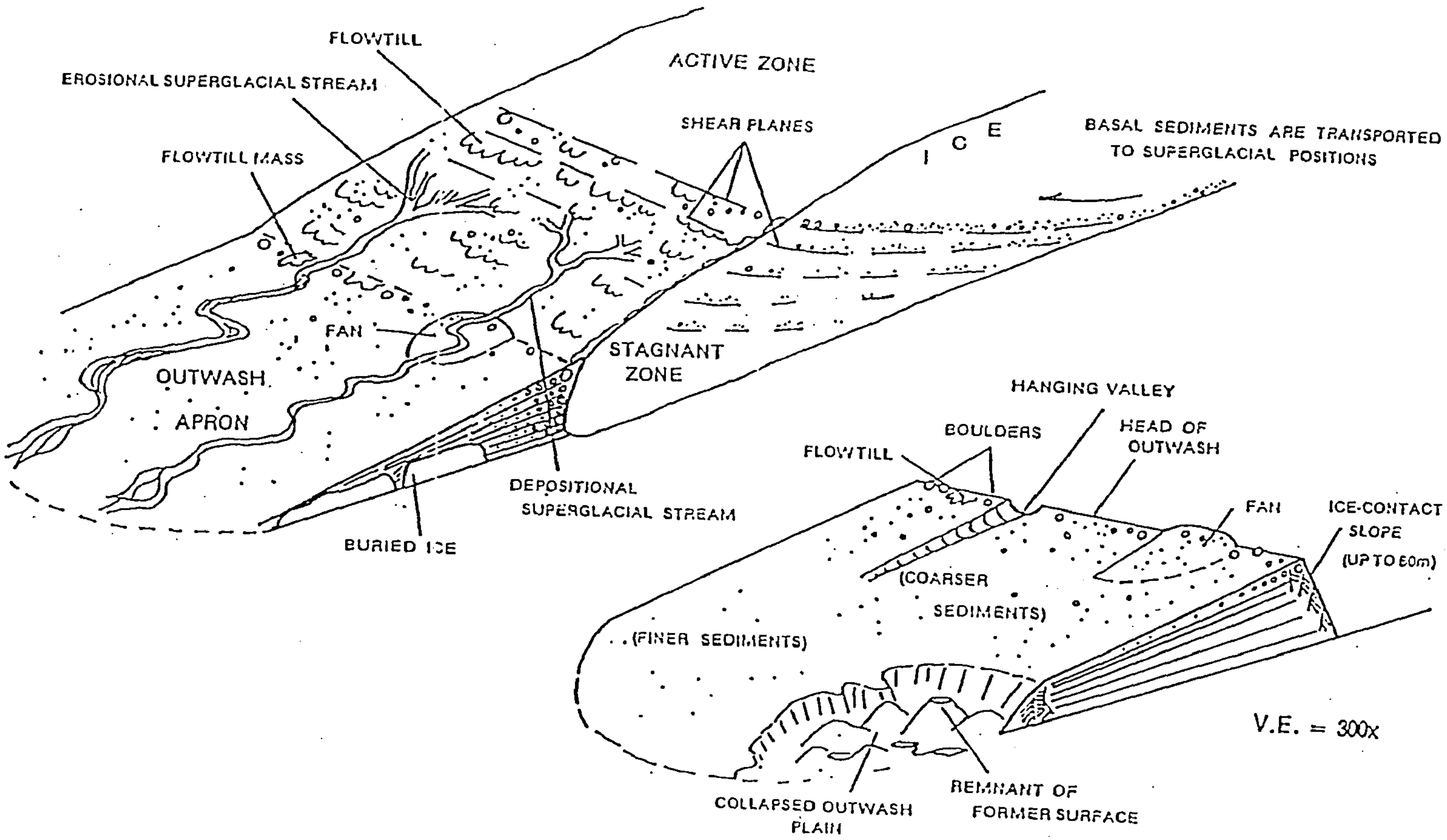

Figure 2. Landforms and sediments associated with a stagnant ice margin (from Blewett, 1984).

The area along the ice margin serves as the head of outwash for the apron. Upon ablation, collapse to the angle of repose occurs, forming an ice-contact slope. Erosional valleys (which later become hanging valleys at the head of outwash) and alluvial depositional fans are formed along the head of outwash as superglacial meltwater and sediments are sluiced from the stagnant zone onto the apron (Fig. 2). Kettles eventually form where masses of ice are buried by outwash.

In addition, crevasse fillings and related features form in the stagnant zone. As the active ice boundary retreats due to thinning, the stagnant zone migrates accordingly, so that a series of stagnation landforms remain with the heads of outwash (major ice-contact slopes with regional trends) delimiting former still stands of the ice margin.

Based on extensive studies of the Malaspina Glacier, Alaska, Gustavson and Boothroyd (1987) present an alternative model of morphosequence genesis in which meltwater "fountains" marking the downstream ends of sediment-laden subglacial and englacial meltwater streams are proposed as the principal source of glaciofluvial deposition. They question the stagnation-zone retreat model of Koteff and Pessl in part because 1) there is no compelling evidence from the literature to suggest that shear planes can supply large volumes of sediment to superglacial locations, and 2) the volumes of superglacial drift present on most glaciers is insufficient to account for the associated thick outwash deposits observed.

Despite uncertainties as to the genesis of morphosequences, the concept provides a basis for analyzing terrain and sediments associated with the Inner and Outer Port Huron Complexes. Evidence supporting its application in this study is provided in the chapters to follow.

<u>Techniques</u> - This study uses the morphologic and sedimentologic characteristics of the region to describe and interpret morphostratigraphy, rock stratigraphy, and time stratigraphy as defined by Willman and Frye (1970).

ROCK STRATIGRAPHY - Willman, Swann, and Frye (1958, p. 5) state that "rock-stratigraphic units are defined and recognized on the basis of observable lithology ... The objective of rock-stratigraphic classification is the recognition of significant lithologic changes in the rock sequence that may be used to establish a framework for stratigraphic description." Although rock stratigraphic units have been formally defined for the Pleistocene in other states such as Ohio, Indiana, and Illinois (for example, see Willman and Frye, 1970), none have been formally identified in Michigan. The present study presents detailed lithologic data on glacial deposits as a means of investigating present topography and as a foundation for future research, but proposes no formal rock-stratigraphic units. Methods of sediment analysis are provided in the appendices. Unless otherwise noted, textural terms such as "sand," "gravel," etc. are used in their generic sense, rather than in accordance with the Wentworth classification or U.S Dept. of Agriculture terminology. Where specific terms are intended the Wentworth classification is employed. The term "till" is used instead of "diamicton" in order to avoid any confusion as to the interpretation of these deposits.

MORPHOSTRATIGRAPHY - Willman and Frye (1970, p. 43) define a morphostratigraphic unit as "a body of rock that is identified primarily from the surface form it displays; it may or may not be distinctive lithologically from contiguous units; it may or may not transgress time throughout its extent." This research uses morphologic criteria as described by Koteff and Pessl (1981) to define the extent of nine principal ice marginal positions within Leverett and Taylor's Port Huron Morainic Complex in northwestern southern Michigan.

Detailed topographic map analysis (1:24,000 and 1:25,000 scale) constituted an important part of this study and included construction of topographic profiles, tracing of contours, and preliminary landform classification. Aerial photography was also used to analyze details of the landscape and as an aid in locating exposures. Field observations were made from passable roads and on foot. All were used in delineating mappable units, which are defined as landforms with a definable set of geomorphic characteristics.

TIME STRATIGRAPHY - A time-stratigraphic unit is defined as a "subdivision of rocks considered solely as a record of a specific interval of time" (A.C.S.N. Code, 1961; p. 657). Radiocarbon dates are used extensively in establishing time-stratigraphic units for the latest part of the Pleistocene, and this research presents two dates on organic material from separate locations within the Inner and Outer Port Huron Complexes.

Study area

The study area includes parts of Kalkaska, Antrim, Charlevoix, and Otsego Counties, and contains about 1,900 km^2. As mapped by Leverett and Taylor (1915), the Inner and Outer Port Huron features trend generally northeast-southwest in parallel fashion across the region, separated by the Mancelona Plain (Fig. 3).

Reinterpretation of these features requires a modification of Leverett and Taylor's major landform groupings. Four principal physiographic units (Fig. 4) are recognized in the present study:

1. Inner Port Huron Complex (including the Mancelona Plain)
2. Post Inner Port Huron zone
3. Outer Port Huron Complex
4. Fluted Uplands and Through Valleys

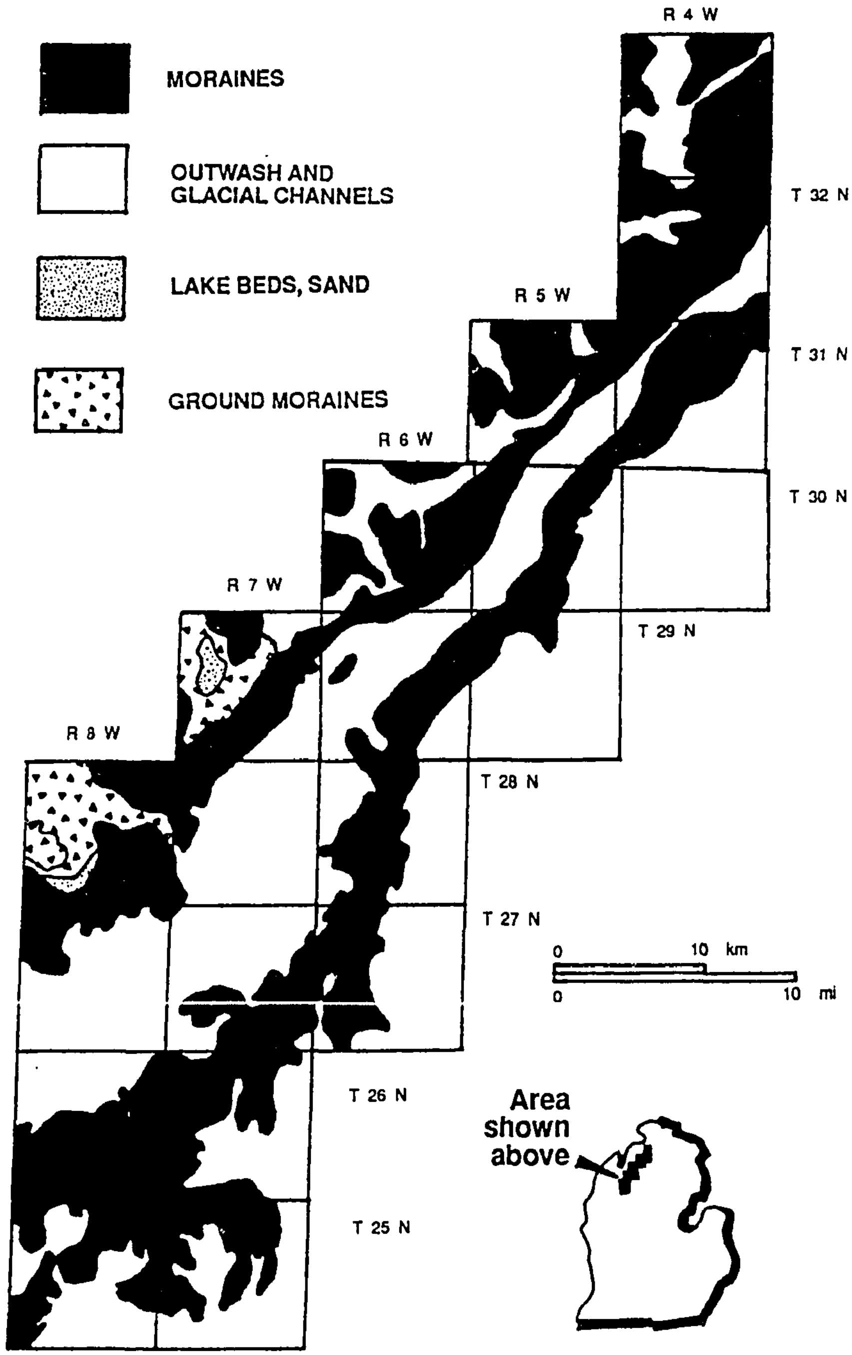

Figure 3. Major landform groups as mapped by Martin (1955).

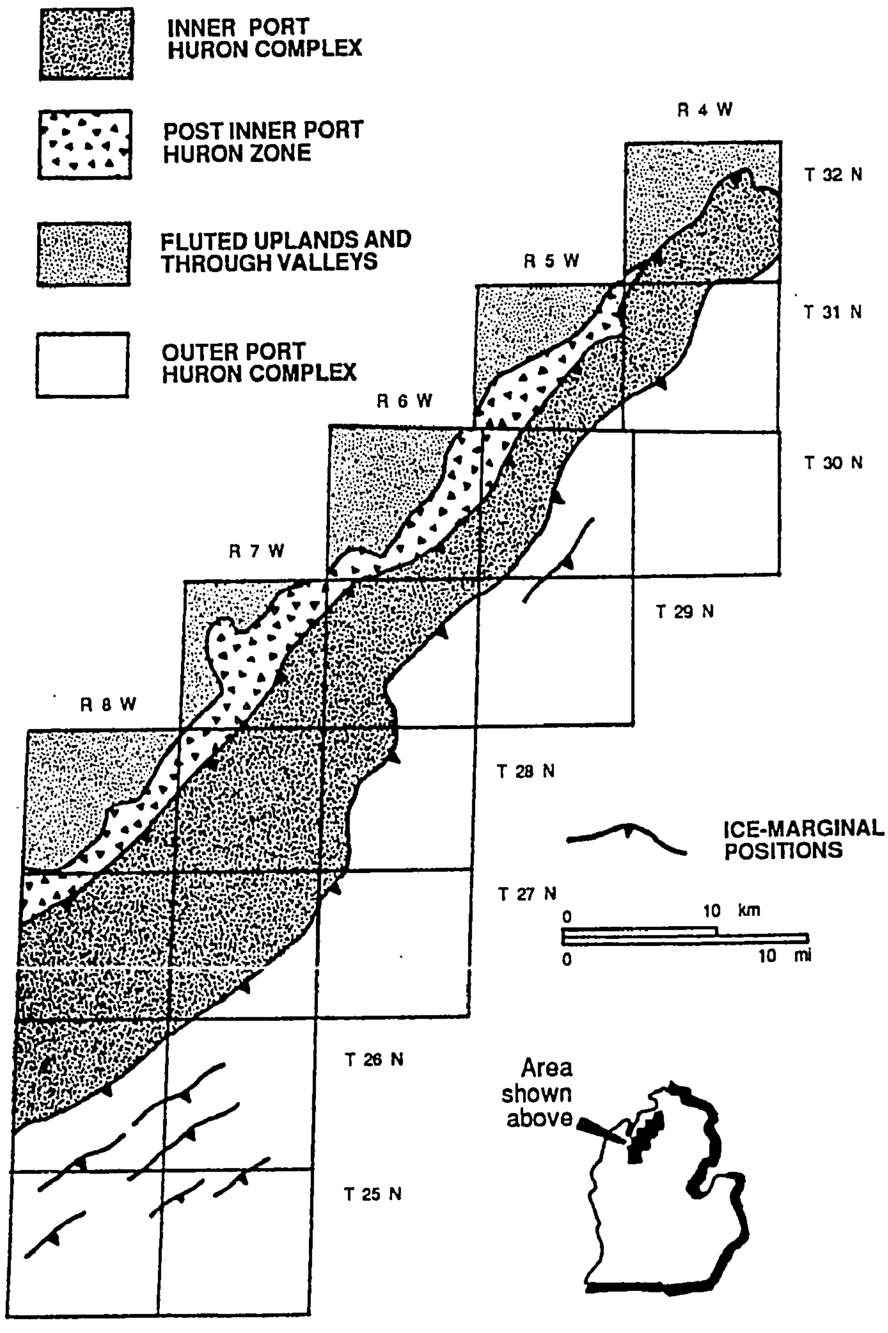

Figure 4. Major landform groups recognized in this study

In the chapters to follow, these regions are discuseed in the order given above. The Inner Port Huron Complex is discussed first because it is of central importance to this study. The closely associated Post Port Huron zone is presented next, followed by the Outer Port Huron Complex. Details of each are provided in Chapter 3. Fluted uplands and associated through valleys are not discussed separately because they are ancillary to the study.

Literature review

Taylor (1897) mapped the Port Huron Complex as a continuous feature, paralleling the Lake Huron coast from Port Huron to the Au Sable River. In a later work, Taylor (1899, Plate II) correlated the Port Huron Moraine for the first time with moraines in northwestern southern Michigan.

Based on these and other studies, Leverett and Taylor (1915) mapped the moraine in a broad arc across the northern part of the Southern Peninsula (Fig. 1). They traced the feature to Muskegon, and correlated it with moraines in eastern Wisconsin. A closely associated, but younger, proximal morainic system, the Manistee, was judged correlative with landforms composed of red till in northeastern Wisconsin.

Leverett and Taylor believed that the Port Huron Complex marked a readvance of the ice. This interpretation, which is still accepted (Karrow and

Calkin, 1985), postulated that a low-altitude glacial lake, Lake Arkona, occupied the southern sections of the Lake Huron basin prior to formation of the Port Huron Moraine. Advance of Port Huron ice into the basin ponded the waters of Lake Arkona and formed a new, higher altitude lake, Lake Whittlesey. Taylor (1905) documented truncation of Lake Arkona beach features by the moraine and showed that Lake Whittlesey was penecontemporaneous with the Port Huron feature.

In northwestern southern Michigan, Leverett postulated that the parallel nature of the Inner and Outer Port Huron Moraines indicated a rather close relationship in time (1915, p. 303). Compared to descriptions of the Port Huron feature elsewhere in Michigan, however, Leverett's narrative on this section of the moraine is quite short. Leverett also published a map of surficial formations in 1924 that included the Port Huron Moraine (though it was essentially unchanged from previous maps), and completed two short reports on the surficial geology of Antrim and Charlevoix Counties (1925a, 1925b).

Bergquist studied glacial deposits in northwestern southern Michigan (Bergquist, 1938, 1940, 1945, 1946, 1952, 1953; Bergquist and Zinn, 1944a, 1944b), and believed that Port Huron till covered an older, highly jointed, well indurated, chocolate-colored clay. He also noted the presence of red till atop Port Huron till in some places.

Subsequent geomorphic study in northern Michigan follows interpretations based on Wisconsin's Two Creeks buried forest (Chamberlin, 1906; Thwaites, 1943). The Two Creeks site consists of a red-gray till grading upward into lacustrine sand and clay, which, in turn grades into lacustrine sand. The buried forest is associated with this sand and overlain by a red clay till interpreted as having been deposited by ice which overrode the forest c. 11,850 ± 100 yrs. B.P. (Broeker and Farrand, 1963). This overlying till was correlated with Valders till, recognized as the uppermost till at Valders Quarry (Thwaites, 1943), 39 km southwest.

The Two Creeks site in Wisconsin is just north of the area where Alden (1918) noted the termination of Glenwood and Calumet beaches by a moraine. He correlated this moraine with Leverett's Manistee Moraine in Michigan, where there is a similar termination of raised shorelines. Based on these relationships and the apparent position of Valders till above the buried forest at Two Creeks, a readvance was proposed. The southward terminus of this advance, named the Valders, lies on an east-west line connecting Manistee and Two Creeks, Wisconsin.

In Michigan, no buried forest of comparable age was found, yet in many places red till overlies a brown till, similar to the stratigraphy at the Two Creeks site. Based on this evidence, plus the termination of raised shorelines by the Manistee Moraine, northern Michigan's red till was correlated with the Valders till at Two Creeks. It was on this basis that the Valders readvance was recognized (informally) in Michigan (Bretz, 1951).

In reconnaissance mapping along the Lake Michigan shore, Bretz (1951) traced red till southward to Muskegon, and extended the Valders limit to this point. He postulated that Valders ice overrode moraines of the Port Huron advance and plastered red till on top of these earlier deposits.

Melhorn (1954) mapped the extent of Valders drift in northern Michigan on the assumption that it had a reddish hue that would distinguish it from brown Port Huron till. However, this work has since diminished in importance with the recognition that Port Huron till may also be red (Farrand, 1976). Like Bretz before him, Melhorn believed that red till of the Valders readvance overlaid Port Huron till. He postulated that Valders ice was obstructed by the high bluffs of the Port Huron Complex and that a thin layer of red till was deposited atop Port Huron sediments, especially in areas of lower elevation. Melhorn did indeed discover red tills overlying brown tills (Port Huron drift) in northeastern Michigan, but he was unable to demonstrate similar associations in the present study area.

Melhorn, in describing the Inner and Outer Port Huron features, indicates that the ridges, at least in places, are composed of stratified drift, including ice-contact deposits. He also reports the presence of high-level lacustrine sediments along proximal sections of the outer feature.

A year later Martin's (1955) surficial geology map of the Southern Peninsula was published. A revision of Leverett's earlier map, it served as the basic cartographic source for nearly 30 years. Martin also published a short popular geology of Grand Traverse County (Martin, 1957).

By 1960, radiocarbon dating had confirmed the Port Huron readvance (Suess, 1954; Flint and Rubin, 1955; Barendsen et al., 1957; Hough, 1958) in Ontario. Based on these dates, Hough assigned an age of 13,000 yrs. B.P. to the Port Huron event.

Research since 1960 has focused primarily on the age and significance of Valders till and its relation to older deposits in northern Michigan and Wisconsin. Interpretations are complicated and still unresolved. Major proposals and complicating factors are reviewed below:

1. A buried bryophyte bed near Cheboygan apparently marks an ice-free interval 13,000 - 12,500 yrs. B.P., before the Port Huron readvance (Cary-Port Huron interstade, Farrand et al., 1969). A single red till above this deposit indicates that the ice front did not retreat appreciably during the Two Creeks interstade (Farrand et al., 1969). Fullerton (1980) questions this interpretation and correlates the bryophyte bed with the Two Creeks buried forest.

2. According to Evenson and Mickelson (1974), the type Valders till (Thwaites, 1943) at Valders Quarry correlates with the till beneath, rather than above, the Two Creeks forest. If true, Valders till is not

Valderan in age. Evenson et. al. (1976) propose the name "Greatlakean" as a replacement for the advance burying the Two Creeks forest.

3. Based on analysis of shorelines and glacial deposits, Evenson (1973) questioned Bretz's notion of a Valders readvance as far south as Muskegon. He maintains that shoreline relationships and correlations described by Leverett and Taylor and by Alden are essentially accurate. If true, this limits the Valders/Greatlakean advance to the area north of the Manistee-Two Creeks line.

4. Both Port Huron and Greatlakean tills in northwestern Michigan are red in color and show similar clay minerology (Farrand, 1976; Monaghan, 1988); the red till boundary mapped by Melhorn (1954) is probably incorrect.

5. Linebeck et. al. (1974) correlate the Inner and Outer Port Huron Moraines with Wisconsin's Shorewood and Manitowoc tills, respectively. In Michigan Taylor (1979, 1981) relates Orchard Lake till to the Port Huron readvance and Filer till to the Greatlakean. These studies are an attempt to establish rock-stratigraphic criteria for Inner and Outer Port Huron deposits.

Burgis (1977) proposed the term "Onaway advance" for Michigan's equivalent to the Valders/Greatlakean stadial. Many landforms studied by Burgis are possible correlatives with the Inner and Outer Port Huron features, and she includes a short discussion of outwash events in the present study area as they relate to drainage in northeastern southern Michigan.

Farrand and Bell (1982) published a map of the surficial deposits of the Southern Peninsula. The Inner and Outer Port Huron Complexes are mapped as "end moraines of coarse-textured till," and boundaries are nearly identical to Martin (1955).

Winters, Rieck, and Kapp (1986) described characteristics of mid-Wisconsinan organic deposits recorded from wells drilled in the Mancelona Plain (details of stratigraphy are discussed in Chapter 2). They state (p. 296) that "the Outer Port Huron Moraine consists mainly of sediments associated with a 'head of outwash'..." Likewise, Anderson and Rieck (1987) briefly note that the Inner and Outer Port Huron features are composed of glaciofluvial sediments and are not end moraines composed of till.

From all these studies there is considerable confusion as to the character of the Port Huron Complexes in the study area. Simply stated, the <u>composition</u>, <u>correlation</u>, <u>age</u>, <u>significance</u>, and <u>detailed relationships</u> of the Port Huron Complex in northwestern southern Michigan are to varying degrees, questionable. No detailed work has been done that establishes precise landform and stratigraphic relationships.

<u>Review of sandar</u> - Because the Mancelona Plain consists primarily of glaciofluvial sediments, it can be referred to as a "sandur." This Icelandic term has long been used to describe certain landforms associated with glaciofluvial deposition. Though spelling of the term varies, "sandur" is generally used as the singular form of the word, while "sandar" denotes the plural form. Sandar have been divided into "valley sandar" and "plain sandar" (Krigstrom, 1962). In North America the former normally has been called "valley train" while the latter

has been referred to as "outwash apron" or "outwash plain."

Major research on sandur processes in areas presently experiencing glaciation are comparatively few, and include works by Fahnestock (1963), Williams and Rust (1969), Rust (1972), Church (1972), Bluck (1974, 1979), Gustavson (1974), Boothroyd and Ashley (1975) and Boothroyd and Nummedal (1978). Sedimentological characteristics have been described by Miall (1977, 1978, 1983), Rust (1978) and Bluck (1979). Miall's 1983 work is noteworthy due to its development of characteristic sediment/structure associations (Scott, Donjek, Platte and Slims types) for delineating specific environmental settings. Though these ideas have been superseded by later work (Miall, 1985), they remain useful in interpreting glaciofluvial environments. The study by Church (1972) includes a detailed and exhaustive coverage of both sandar processes and morphology.

These glaciological studies are useful for interpreting sandar in areas of Pleistocene glaciation such as northwestern southern Michigan. However, few of the process-oriented studies involve sandar formed parallel to the ice margin such as the Mancelona Plain.

Justification

Interpretations of the morphology and genesis of the Port Huron Complex are based primarily on the dated work of Melhorn (1954) and Leverett and Taylor (1915).

Farrand and Bell's (1982) recent mapping of the feature as "end moraine of coarse-textured till" uses areal patterns nearly identical to Martin (1955; in turn based on Leverett and Taylor).

Recent field work and newly available large-scale topographic maps indicate that the area is composed of a complicated assemblage of landforms formed along marginally stagnant, rather than active, ice and that glaciofluvial deposition was by far the most important component in development of the present topography. Indeed, several gravel pits in the most proximal sections of the inner ridge (mapped as moraine by Leverett and Taylor) contain stratified sand and gravels to a depth of 8 meters or more, while topographic map contours display the typical bowed pattern associated with outwash aprons.

R.J. Price (1973, p. 19) has stated:

> There is no excuse for those authors who insist on calling a ridge or a series of mounds of well sorted stratified sand and gravel a moraine, when there is abundant evidence that meltwater rather than ice is primarily responsible for its deposition.

Though Price was mainly concerned with inappropriate terminology, his words emphasize the need for a thorough understanding of landform genesis and the dangers of using "end moraine" to describe features composed of glaciofluvial sediments. Abundant evidence indicates that the Port Huron Moraines are not wholly the product of active ice deposition and are not composed largely of till as the term "moraine" implies. Additional study, based on more modern concepts of glacial geomorphology is needed.

Along with landform genesis and mapping, this study investigates the deglaciation history of northwestern southern Michigan. Farrand and Eschman (1974, p. 46) state:

> ...the key to unravelling the tangled mess of morainic remnants in this area, and working out the details of the series of ice-frontal positions during retreat from the Outer Port Huron, is found in the series of well developed outwash surfaces that represent the various meltwater drainageways, each of which is graded from a moraine ultimately to a proglacial lake stage in one of the bordering lake basins, to the west or east. A careful mapping of these drainageways using geomorphology, lithology, and stratigraphy, will, we believe, eventually give us the ice frontal sequence.

At the very least, this study provides a solid foundation for follow-up work on moraines and outwash surfaces in the northwestern part of the Southern Peninsula. More important, it reveals, for the first time, detailed morphologic, stratigraphic, and chronologic relationships within the Port Huron Complex and provides an improved understanding of glacial and post-glacial events in this part of Michigan.

Chapter 2

PALEOZOIC BEDROCK AND QUATERNARY SEDIMENTS ASSOCIATED WITH THE INNER AND OUTER PORT HURON COMPLEXES: REVIEW AND NEW FINDINGS

BEDROCK GEOLOGY

Paleozoic sedimentary rocks, described by Martin (1936), Landes and Ehlers (1945), Fischer (1969), and Milstein (1987), underly thick drift in the study area (Fig. 5). Subcropping lithology consists primarily of the transitory Ellsworth and Antrim formations of the Devonian and Mississippian periods and the Mississippian Coldwater and Marshall formations. Regionally each unit dips southeastward toward the center of the Michigan structural basin; structure, however, may vary locally.

The Ellsworth and Antrim formations overlie the Traverse group (Devonian) and actually occupy the same stratigraphic position, their differences being the product of a facies change. Ellsworth Shale exists in northwestern southern Michigan and is a soft, semi-indurated green shale with bands of calcareous material. The thin-bedded and fissile Antrim Shale is located in northeastern southern Michigan and consists of cinnamon-brown, dark gray-black shale with nodules of limestone and pyrite. Ellsworth Shale crops out at several places

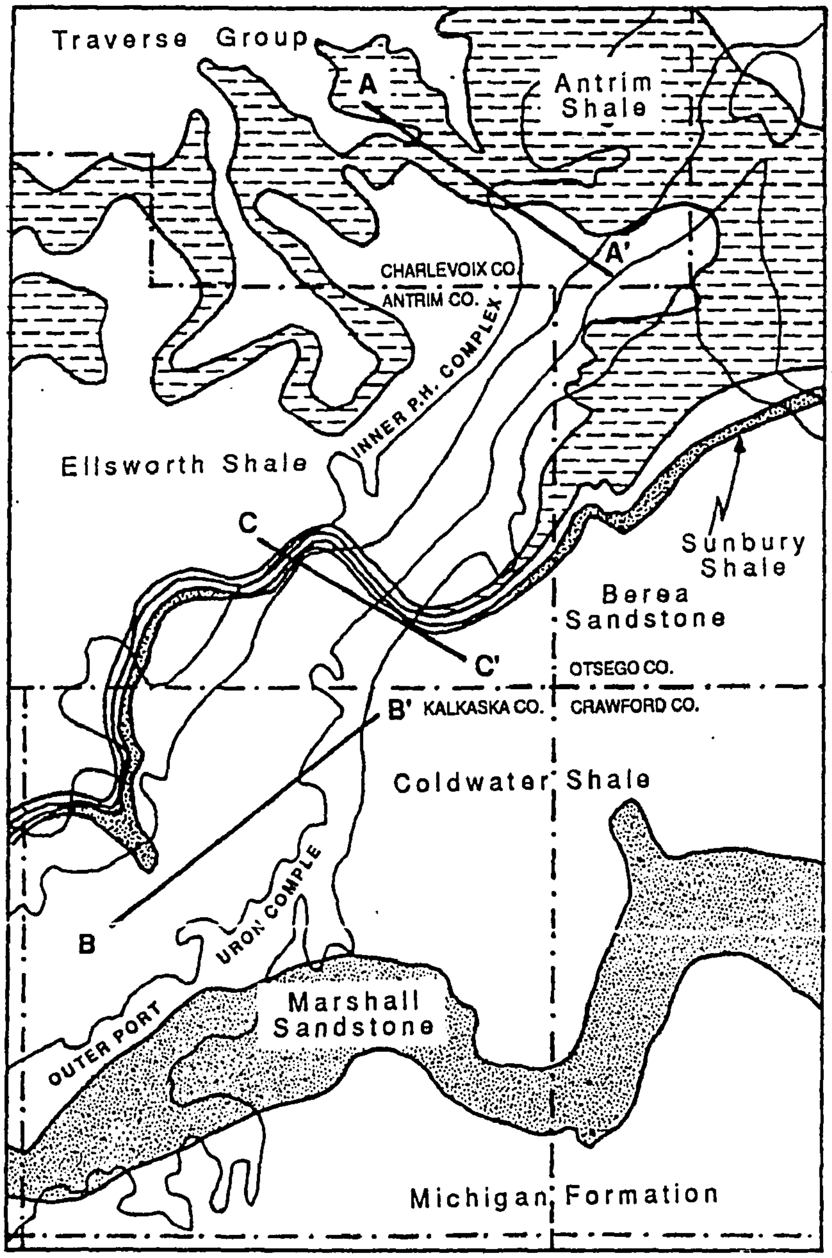

Figure 5. Bedrock geology (from Milstein, 1987), showing the relationship with the Inner and Outer Port Huron Complexes.

in western Antrim and southern Charlevoix counties; its type section is in the Ellsworth Quarry.

The overlying Coldwater Shale and Marshall Sandstone are not exposed in the study area. Where reached by wells, Coldwater Shale is variable in color and contains scattered sandy lenses. Marshall Sandstone consists of light gray to white sandstone with shale partings (Melhorn, 1954).

Altogether, these rocks help define the lower boundary of Quaternary deposits in the study area. Characteristics of the bedrock surface and its relation to topography are discussed below.

BEDROCK SURFACE

Recently compiled but unpublished maps of bedrock topography for Antrim, Charlevoix, Otsego, and Kalkaska Counties were generously provided by Dr. R.L. Rieck for use in this study (Rieck, various dates; 1:63,360 scale; 50 foot contours). Based on an examination of thousands of well logs, these maps furnish the most detailed bedrock information now available, and provide a basis for regionalizing its surface. In the discussions below data are presented in feet in order to match Figure 6.

Bedrock topography

The undulating, high relief (500-800 ft, 150-245 m) bedrock surface (Fig. 6) can be divided into the following four sections: 1) elliptical uplands separated by interconnected valleys in east-central Charlevoix

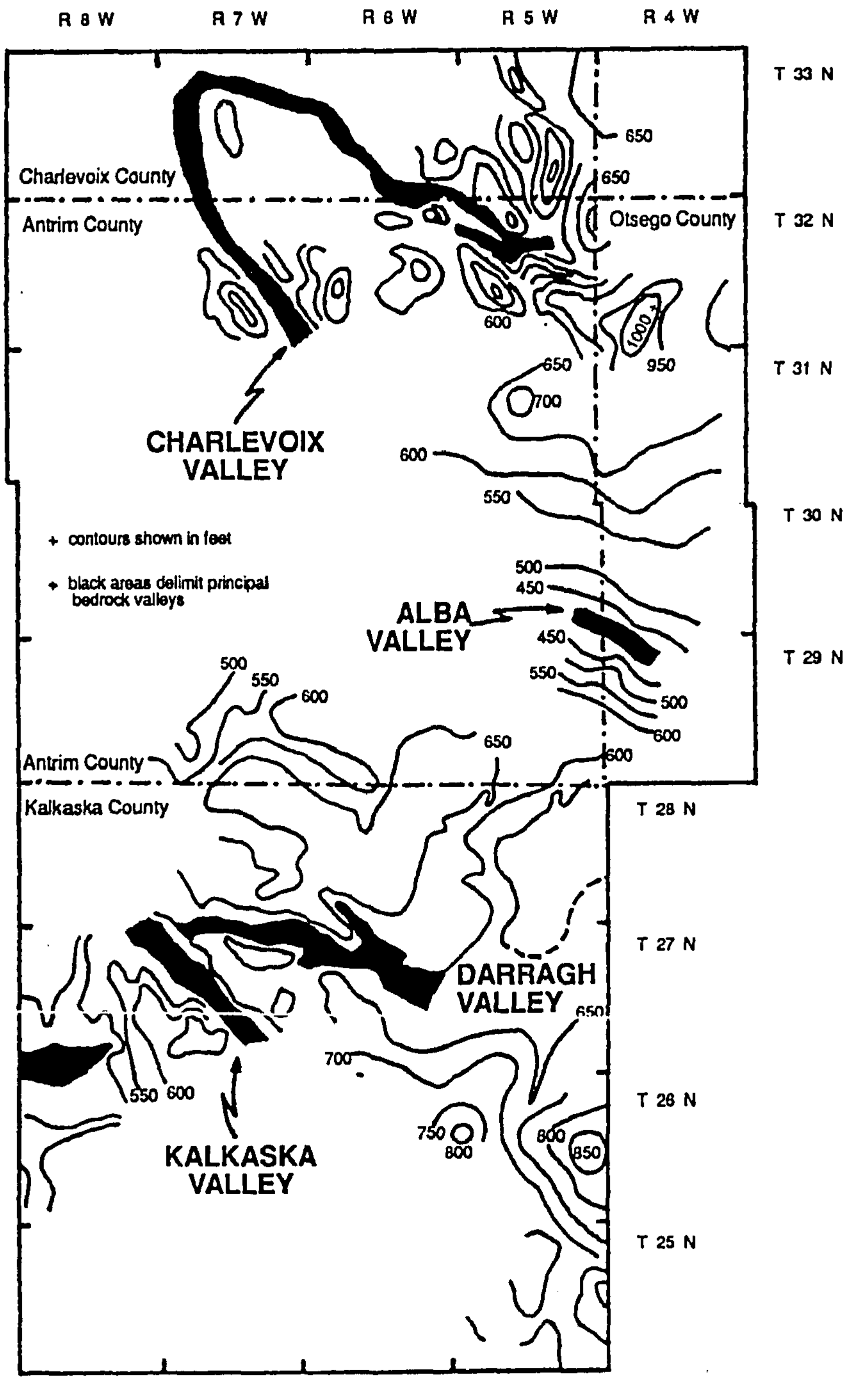

Figure 6. Bedrock topography (©1981, 1985, R.L. Rieck; used with permission).

County, 2) a relatively high altitude (1000 ft, 305 m) region in extreme southeastern Charlevoix County, 3) east-west trending lowlands east of Alba and, 4) a plateau-like tract, about 650-700 ft (200-215 m) in altitude, punctuated by northwest-southeast trending linear valleys in Kalkaska County.

Bedrock valleys

Four notable bedrock valleys, informally named the Kalkaska, Darragh, Alba, and Charlevoix valleys, lie buried beneath drift in the study area. Kalkaska Valley is oriented northwest-southeast and is located principally in T. 27 N., R. 7 W. Thalweg depth averages 345 ft (105 m) below adjacent bedrock uplands but may exceed 600 ft (180 m) toward the northwest. Darragh Valley, which is relatively shallow, trends east-west along the northern boundary of T. 27 N., R. 7 W. and averages 130 ft (40 m) in depth. The east-west oriented Alba Valley straddles the Antrim-Otsego County line in T. 30 N., R. 5 W. and T. 30 N., R. 4 W. and is about 150 ft (45 m) deep. Charlevoix Valley trends northwest-southeast across T. 32 N., R. 5 W. and is associated with the interconnected valleys and elliptical uplands already described.

Rieck and Winters (1979) attributed buried linear bedrock lowlands elsewhere in Michigan to modified preglacial stream valleys. Pattern and form of bedrock valleys in the present study suggest a similar genesis.

Regional, preglacial drainage patterns here have yet to be determined due to 1) the uneven distribution of data points, 2) paucity of tributary valleys that might indicate flow direction, and 3) the unknown amount of glacial modification that has occurred. Reconstructions of preglacial drainage elsewhere by other workers (Dorr and Eschman, 1971) postulate a major north flowing river system in what is now the Lake Michigan basin that favored drainage to the northwest in the study area. Evidence supporting this conclusion includes 1) a bedrock surface that becomes lower toward the northwest, and 2) bedrock valleys that tend to deepen in the same direction. Thus, preglacial streams in western Kalkaska, Antrim, and Charlevoix Counties most likely flowed toward the northwest.

RELATIONSHIP OF THE BEDROCK SURFACE TO TOPOGRAPHY

North of Mancelona, surficial topography mimics the bedrock surface but displays higher relief (Fig. 7). Conspicuous, northwest-southeast oriented flat-bottomed lowlands, called "through valleys" in this study, are aligned with similarly oriented bedrock valleys. In addition, the northernmost tracts of the Inner Port Huron Complex (named the "apex" in this dissertation; Fig. 4) coincide with the highest known bedrock altitude in the study area (T. 32 N., R. 4 W.; Fig. 6). South of Mancelona, however, localized relationships between bedrock and surficial topography are weak or non-

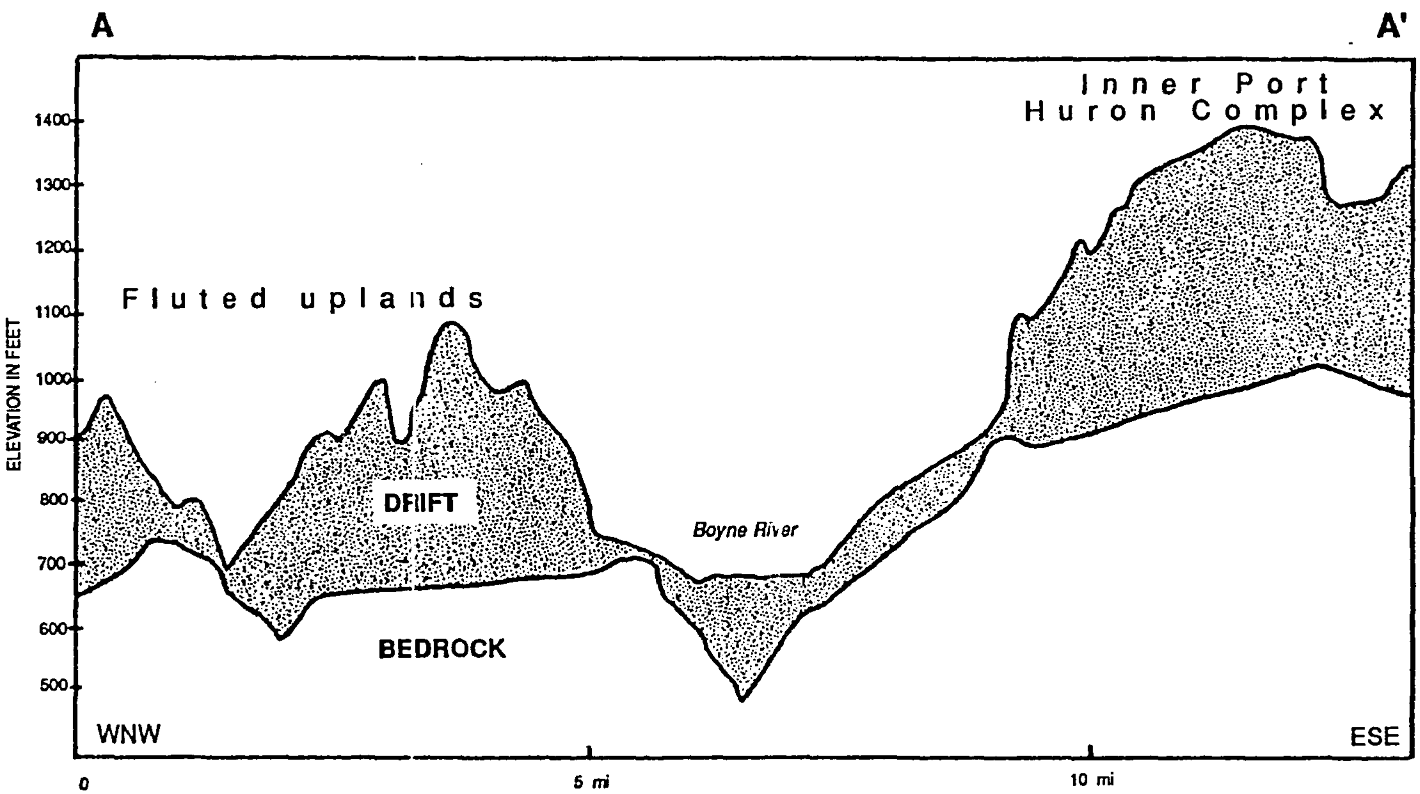

Figure 7. Profile A-A,' shown on Figure 5, showing the relationship of the bedrock surface to topography.

existent (Fig. 8). Kalkaska Valley, so conspicuous on the bedrock surface map, is completely masked at the surface.

Melhorn (1954, p. 29) states that:

> initial variations in (hardness and lithology) probably produced a preglacial topography in which a northward-facing cuesta had been developed on the Marshall Sandstone. This cuesta faced a lowland belt to the north developed on softer Antrim, Ellsworth and Coldwater Shales...Glacial erosion and deposition modified (the bedrock) pattern but did not completely obscure it, so that the old topographic relationships are still evidenced in lesser degree on the present surface. For example, the Port Huron moraine throughout the region closely follows the approximate position of the scarp fronting the old Marshall cuesta.

Though reasonable, this interpretation is not substantiated by bedrock surface data. Uppermost bedrock altitudes from T. 26 N., R. 6 W., underlain by the Marshall Formation (Milstein, 1987), average 230 meters. In the adjoining township (T. 27 N., R. 6 W.) altitudes on the Coldwater Shale average 195 m and there is a gradation of bedrock altitudes across the lithologic boundary, rather than a distinct escarpment. This apparent absence of a Marshall cuesta in the region is not easily explained, but indicates factors other than local configuration of the bedrock surface may be responsible for positioning of the Port Huron Complex.

In addition, Melhorn's quote implies that the Port Huron feature closely parallels the pattern of subcropping lithologies. Martin's map of bedrock geology (1936), which Melhorn cited, shows the northern boundary

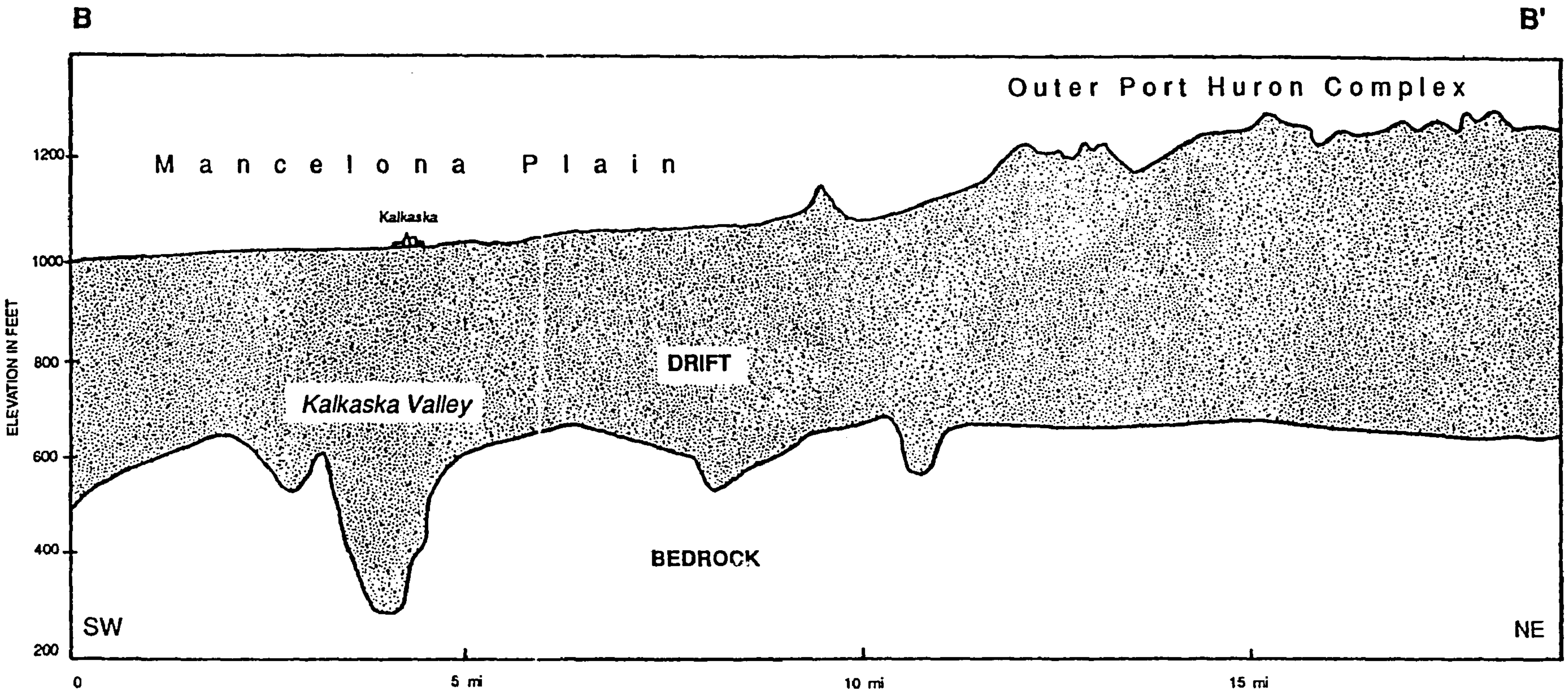

Figure 8. Profile B-B,' shown on Figure 5, showing the relationship of the bedrock surface to topography.

of the Marshall formation trending southwest-northeast across Kalkaska and Otsego Counties, somewhat paralleling the trend of the Outer Port Huron feature. The latest geologic map (Milstein, 1987), based on more detailed information, shows a much different boundary, oriented east-west through Kalkaska and Crawford Counties; only in southwestern Kalkaska County does the trend coincide with the Outer Port Huron position. Certainly, the Port Huron Complex broadly parallels the trend of the Michigan structural basin, but in detail the two Port Huron margins extend across three lithologic units (Marshall, Coldwater, Ellsworth/Antrim formations; Milstein, 1987). This suggests that bedrock influences on topographic positioning are variable, and that subcropping lithology alone cannot acount for the location of the Port Huron Complex.

In short, the apparent absence of the Marshall cuesta and poor relationship between bedrock and surficial topography indicate that local bedrock characteristics were not significant factors in controlling placement of the Outer Port Huron trend in the south (arguments for regional bedrock control of the feature are presented in Chapter 3). North of Mancelona, however, bedrock topography exerted a significant influence on the modern landscape, as indicated by coincidence of both surfaces, and correspondence of high bedrock with the Inner Port Huron apex. Thus, the Port Huron Complexes exhibit strong contrasting relationships between bedrock topography and modern terrain in northern versus southern parts of the study area.

RELATIONSHIP BETWEEN THROUGH VALLEYS AND BEDROCK VALLEYS

Bedrock valleys apparently have influenced placement of modern through valleys, even in areas where average drift thickness exceeds 100 meters. Modern glaciated landscapes which reflect details of an older, buried Pleistocene paleo-surface have been called "palimpsest" by Rieck and Winters (1979). They attribute such relationships in southeastern Michigan to first the accumulation and later the ablation of ice in pre-existing stream valleys (Fig. 9). Eventually this process creates a lowland overlying the old bedrock channel. Repeated glaciations may result in a series of valleys stacked one on top of the other, each reflecting the trend of the original valley. Such a process may also explain coincident valleys in thick drift in the study area. If so, the presence of palimpsest topography in Charlevoix and Antrim Counties expands the application of this concept in glaciated regions.

CONCLUSIONS

Trend of the Inner and Outer Port Huron Complexes (Fig. 5) appears to be unrelated to subcropping bedrock lithology, as mapped by Milstein (1987). However, bedrock topography probably does control the location of

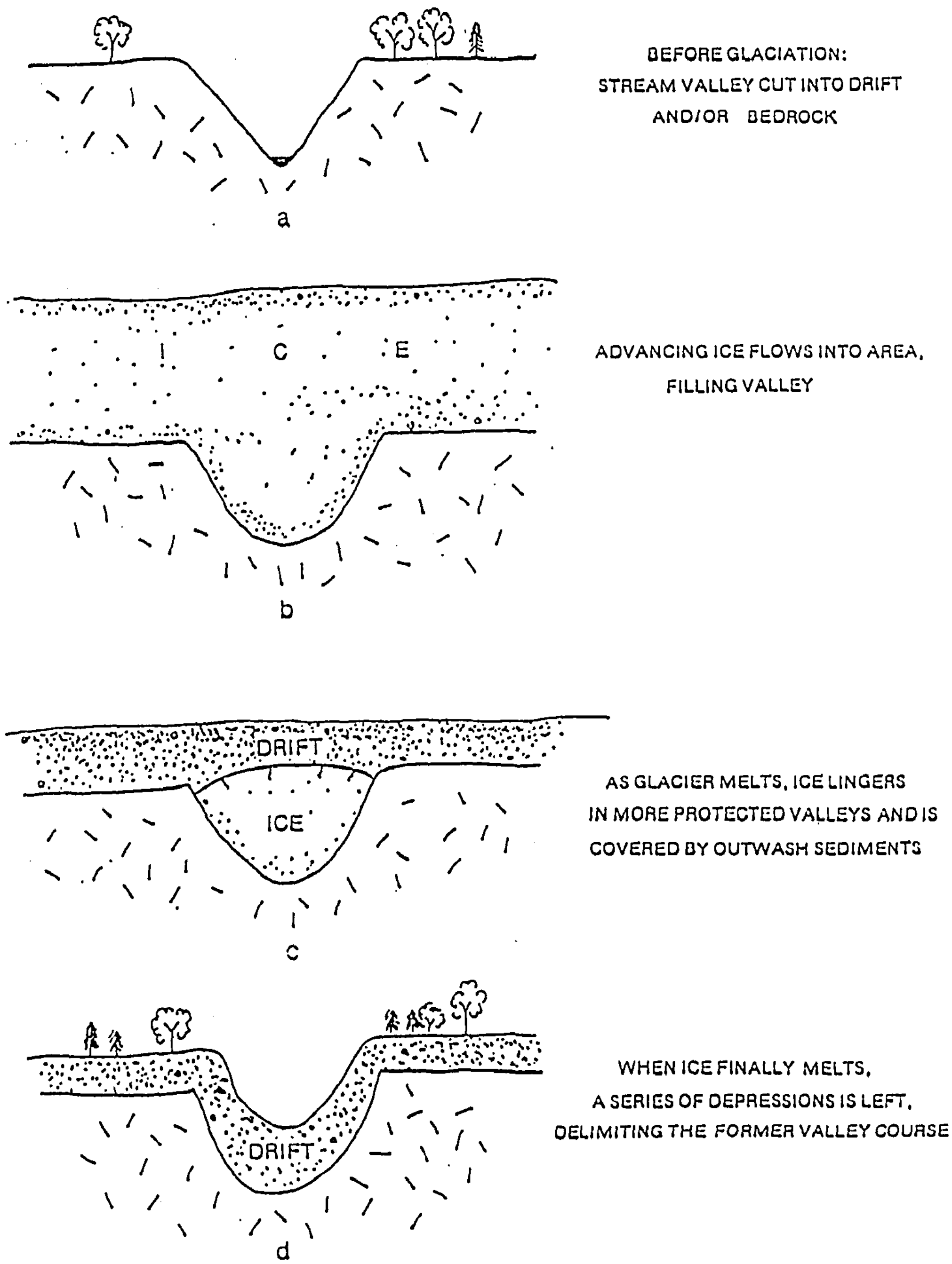

Figure 9. Proposed genesis of coincident valleys (from Blewett, 1984).

the Inner Port Huron apex, and influences the topography in eastern Charlevoix, western Otsego, and northern Antrim Counties. In addition, evidence presented in Chapter 3 documents a strong relationship between bedrock lowlands and regional landform patterns of the Inner and Outer Port Huron features.

SEDIMENTS ASSOCIATED WITH THE INNER AND OUTER PORT HURON COMPLEXES

Application of the morphosequence concept here requires 1)identification of facies changes for the Inner Port Huron and Outer Port Huron features, plus 2) evidence that ice-contact and proglacial glaciofluvial sediments, rather than till, are the major surficial deposits in areas previously mapped as moraine (Leverett and Taylor, 1915; Farrand and Bell, 1982). Both detailed mapping and sediment analysis were necessary for this part of the investigation.

Aspects of Pleistocene stratigraphy and drift thickness were analyzed from water and petroleum well logs on file at the Geological Survey Division of the Michigan Department of Natural Resources. Surficial sediment data were derived from gravel pits, soil maps, stone piles, roadcuts, and other exposures.

Drift thickness

A drift thickness map for the area, based on approximately 400 well log data points and supplemented with data from R.L. Rieck (1981, 1985; used with permission), is shown in Figure 10. Contours are drawn in feet to match the well log data and the values provided by R.L. Rieck. Average thickness is 550 feet (170 m), and the maximum (953 ft, 290 m) is over the deepest valley on the bedrock surface. Thickness contours trend perpendicular to the Inner and Outer Port Huron margins, and values tend to increase northeastward, reaching a maximum of 843 ft (257 m) in T. 32 N., R. 4 W. at the Inner Port Huron apex. These trends are somewhat misleading, however, because although individual thickness values are highest toward the north, average values become greater toward the south (Figs. 7 and 8). This relationship is obscured in Figure 10 because the number of data points is insufficient to show greater drift thickness variability in northern areas.

As revealed by a comparison of Figures 3 and 10, variations in glacial deposit thickness do not correspond with locations of prominent topographic features. This suggests that drift thickness alone is inadequate to explain trends of major topographic elements in the study area, with the possible exception of the Inner Port Huron apex.

Relation of drift, bedrock form, and modern topography

The study area can be subdivided into northern and southern sections based on drift/bedrock relationships.

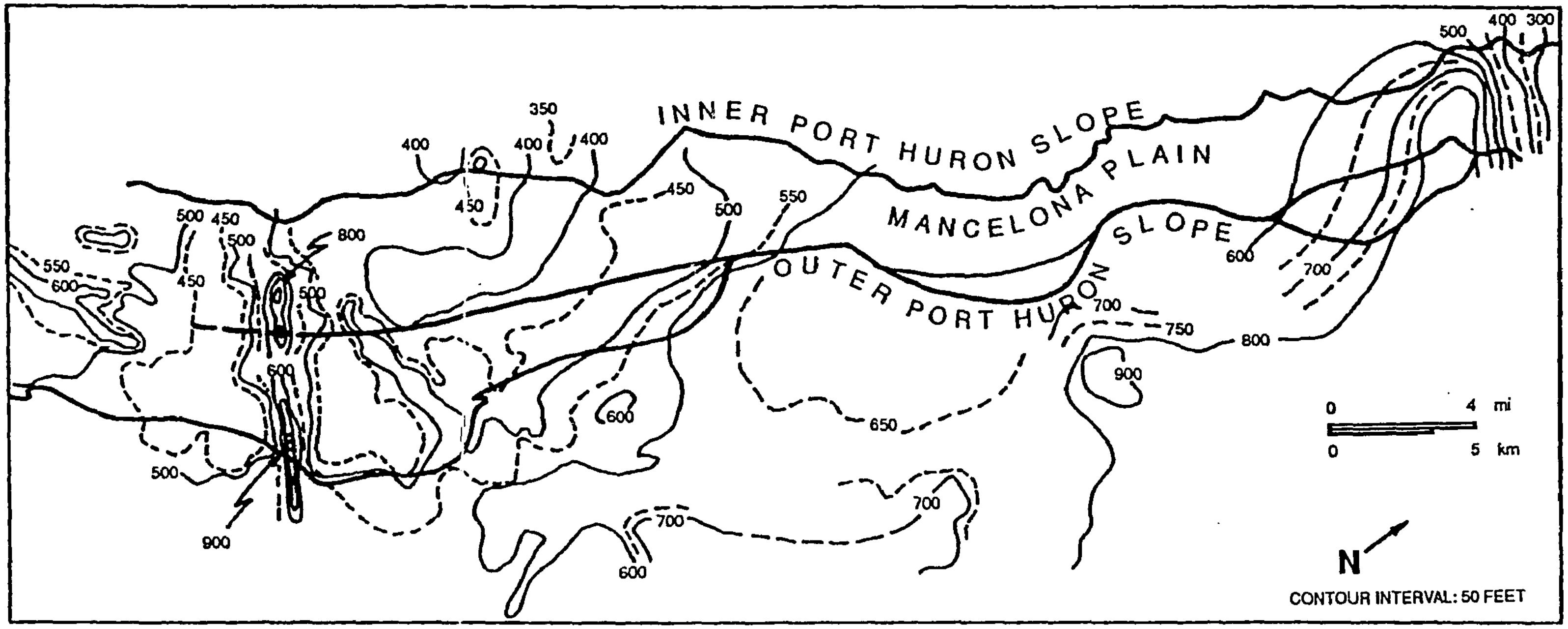

Figure 10. Drift thickness in the Inner and Outer Port Huron Complexes

South of Mancelona glacial sediments obscure bedrock surface characteristics and related valleys are identified only as linear areas of thick deposits on the map. In contrast, bedrock topography and drift thickness show strong correspondence north of Mancelona. Thick glacial sediments at the Inner Port Huron apex mimic high bedrock in the subsurface (Fig. 7); thin deposits cover adjacent bedrock valleys.

The Alba bedrock valley appears to mark a transition between northern and southern sections. Although this valley is deeply buried, it is expressed at the surface in the form of kettle chains and dry channels.

Regional differences in drift/bedrock relationships may be related to a particular thickness threshold of glacial deposits, which, once exceeded, works to mask irregularities in bedrock topography. Meek (1984) found that topographic expression of the bedrock surface is a function of bedrock relief and drift thickness as expressed in the form:

$$T \propto \left(\frac{Rb}{2} + 10 \text{ meters} \right)$$

where T=average drift thickness in meters and Rb=maximum bedrock relief in meters. When T exceeds the right side of the equation, then the form of the underlying surface likely will be masked. If T is less, bedrock form will be reflected in present topography.

Data from the study area substantiate application of these findings in part:

North of Mancelona

$T = 64$ m $Rb = 183$ m

$64 < 101.5$ m

The form of the bedrock surface will be evident in the topography.

South of Mancelona

$T = 156$ m $Rb = 131.1$ m

156 m > 75.6 m

The form of the bedrock surface will be masked at the surface.

Though these equations were developed for localized areas with thinner drift (15-35 m), they do present a reasonable accounting for bedrock/drift relationships observed on the Inner Port Huron feature.

Subsurface stratigraphy

Water and petroleum well logs provide the bases for limited interpretations of subsurface stratigraphy in the Inner and Outer Port Huron Complexes. A few outcrops along the deeply incised Rapid River provide verification for some of these interpretations, and an exposure near Rugg Pond reveals a Pleistocene paleosurface recognized on the basis of glacially buried wood and other organic matter that has been ^{14}C dated. All are discussed below.

SUBSURFACE SEDIMENTS ASSOCIATED WITH THE INNER PORT HURON COMPLEX

Figures 11 and 12, which are based on data from about 200 well logs, show, respectively, the thickness of uppermost sand and gravel deposits, and variations in the underlying clay surface within the study area. Average thickness of the uppermost sand and gravel unit is from 150 ft (45 m) in proximal regions (areas closest to the Inner Port Huron crest) to less than 40 ft (10 m) distally (areas farthest from the crest). Maximum values exceed 270 ft (80 m) at the Inner Port Huron apex and 170 ft (50 m) northwest of Mancelona. The Kalkaska and Darragh bedrock valleys also display thick sediments. A small, high-altitude terrace (Camp Ten surface, chapter 3) has thicker deposits along its northwest margin.

Volume of the uppermost sand unit in the study area is approximately 6 km^3 based on the expression $V=1/2(l*w*h)$, where V=volume, l=length of the sandur, w=width of the sandur, and h=thickness of deposits at the Inner Port Huron crest.

Figure 13 uses combined data from Figures 11 and 12, and shows that upper sand and gravels were deposited upon clay with a surface of moderate relief (165 ft, 50 m) that is inclined northwestward. Implications of this are discussed in Chapter 4.

Collectively, four lines of evidence suggest that the underlying clay is till:

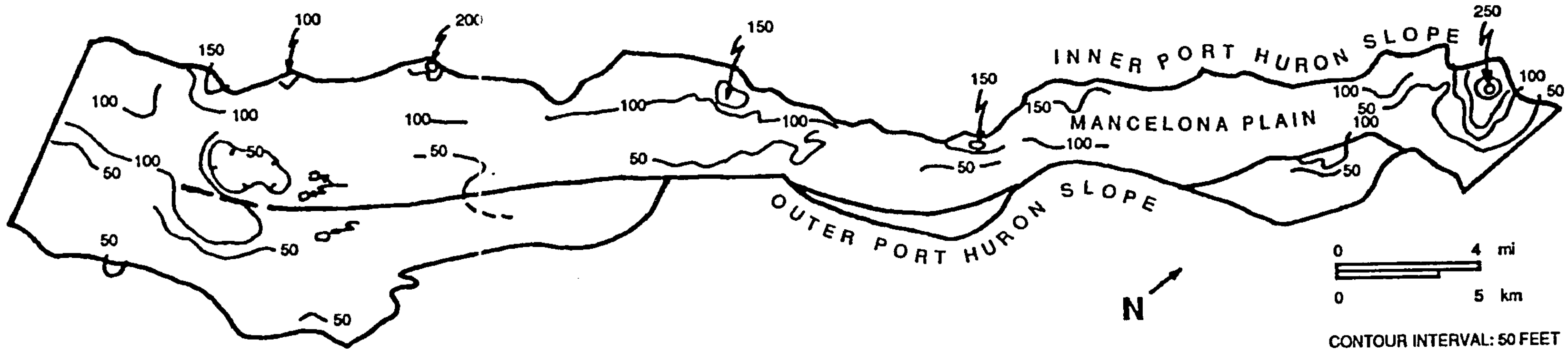

Figure 11. Thickness of the uppermost sand and gravel unit.

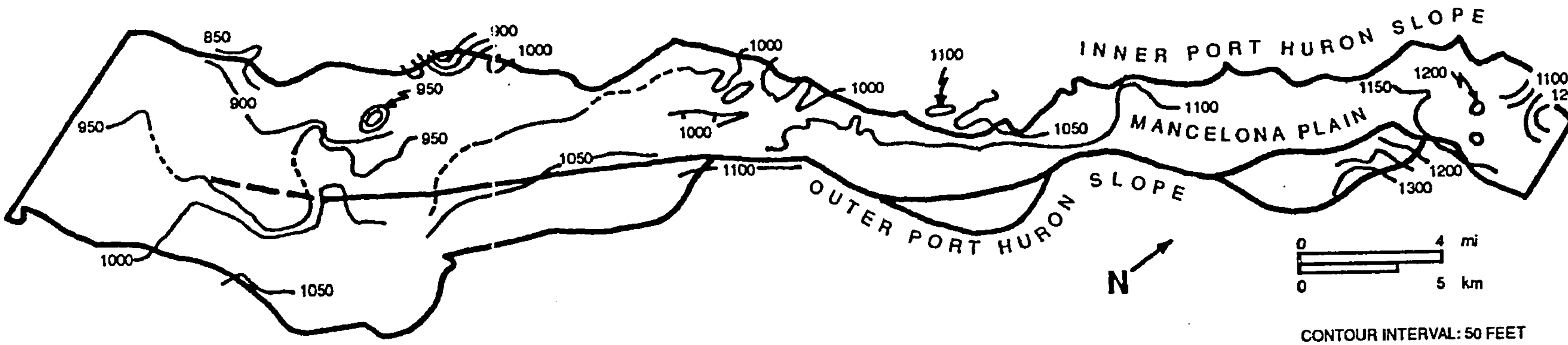

Figure 12. Altitude of the underlying clay surface.

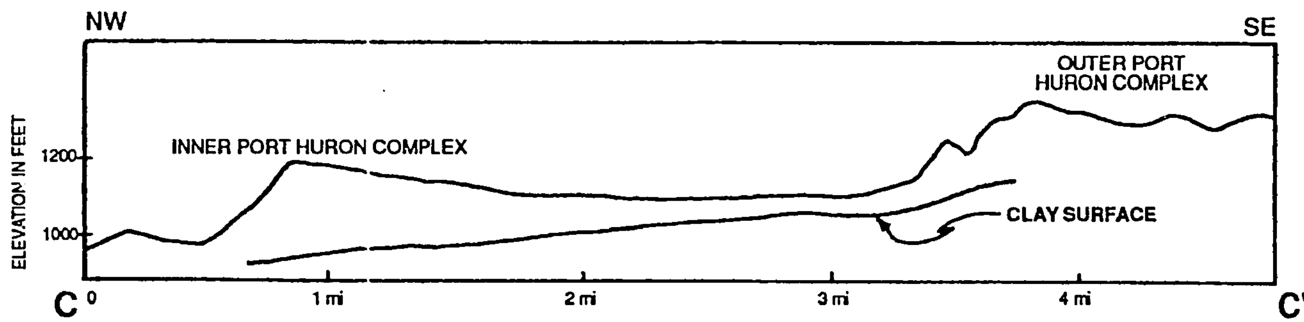

Figure 13. Relation between modern topography and the underlying clay surface. Profile location shown in Figure 5.

1) brown till is exposed along the west side of the Rapid River Valley (SE1/4, SW1/4, T. 28 N., R. 7 W.) at an elevation of approximately 282 m, well within the range of altitudes for the highest clay surface here (275 - 290 m; Fig. 12).

2) samples from two gas wells on the Mancelona Plain reveal that till is beneath the uppermost sand and gravel unit at altitudes comparable to those reported in the study area (Winters et al., 1986).

3) In places, underlying clay surfaces appear to be lineated in a northwest-southeast direction (based on contour patterns; Fig. 12) and may represent buried equivalents of streamlined landforms present in the modern landscape in northwestern Antrim County.

4) valleys on the clay surface correspond with axes of major bedrock valleys (Fig. 12). This is accommodated most simply by uniform deposition of basal till upon a pre-existing surface.

A more complicated mode of deposition is required if these clays are lacustrine. First, such extensive lacustrine deposits probably formed in an ice-free or ice-marginal environment, rather than subglacially. Second, because unaltered surfaces of lacustrine deposits are usually flat, any valley existing on this surface must be a) cut by subsequent stream erosion during or after draining of the lake, or b) form subaerially by melting of ice blocks buried in pre-existing lowlands prior to lake formation. Once formed, this valley must then be buried by sand and gravel. Though possible, this model seems overly complicated compared to simple deposition of till.

SUBSURFACE SEDIMENTS ASSOCIATED WITH THE OUTER PORT HURON COMPLEX

Subsurface clay deposits are highly variable in the Outer Port Huron Complex, making analysis difficult. Only in the Outer Port Huron apex (T. 31 N., R. 4 W.) is any significant underlying clay pattern identified. Here, clays are concentrated at depth beneath the crest of the Outer Port Huron feature and are absent distally. Their 1) relatively shallow depth (4-7 m) and 2) close association with stagnation topography and stratified sediments suggest that these clays may be flow or ablation till. An exposure of till at Fleming's farm, discussed below, supports this interpretation.

South of the apex, distributions are even more complicated. Logs rarely record clay beneath the proximal tracts of the Outer Port Huron Complex east of Elmira, where some wells are 93 m deep. Most logs from wells east of Alba do, however, report numerous clay layers separated by sand and/or sand and gravel. Clay has also been logged at depths of 50-60 m in regions of the Outer Port Huron feature south of Alba airport. The pattern here may be related to successive positions of the ice margin in this area (Lakes of the North margin;

Ch. 3). East of Mancelona the surface varies from 15-70 m in depth, with a mode of approximately 35-40 m. South of Crawford Lake clays are widespread in the subsurface and tend to be less deeply buried.

Combined with altitudes of the modern surface, elevations of the subcropping clay surface define the thickness of the uppermost sand and gravel unit comprising the Outer Port Huron Complex. Variability of clay distributions here makes interpretation difficult, but, in general, this higher unit forms a wedge-shaped deposit thickest in proximal regions. Farther south this wedge is less well defined.

RUGG POND SITE

Glacially buried organic deposits are exposed 5 m above the base of the bluff immediately north of Rugg Pond Dam (SE1/4, NW1/4, NE1/4, sec. 31, T.28N., R.7W.) in northern Kalkaska County. Flattened wood fragments and other carbonaceous materials are within a silt lying between two brown tills (10 YR 7/2, Fig. 14). The wood yielded a ^{14}C date of >41,000 yrs. B.P. (Beta - 29495); preliminary analysis of a related pollen assemblage (Marlette, unpublished material, 1989) indicates accumulation under northern boreal or subarctic conditions. Layers containing carbonaceous material dip 45 degrees toward the north at the exposure's northern edge, indicating that the deposits have been deformed.

The stratigraphy associated with the Rugg Pond site is shown in Figure 14. Nearly two thirds of the outcrop consists of lacustrine fine sand and silt. Till lenses are 1) thin, 2) usually separated by sand and silt deposits, and 3) confined to the lower parts of the exposure. Till 1 lies highest in the column and is not associated with the organic material. Till 2 is directly above the organic-bearing silts, and till 3 lies underneath.

Although stratigraphic data are limited because of the small size of the outcrop, till 2 may mark a pre-Late Wisconsinan ice advance because it buries wood greater than 41,000 years old associated with "cold" pollen. Age and depositional history of tills 1 and 3 are unknown; color and textural similarities between tills 3 and 2 suggest that they may be part of the same deposit. In addition, this outcrop and related sediments demonstrate the great abundance of ice marginal deposits (as opposed to till) in this part of the Inner Port Huron Complex, a finding in agreement with detailed stratigraphy for thick sections of drift (+ 100 m) in the area as reported by Winters et al. (1986). Figure 14 shows that only about 25% of the stratigraphic column is till, with the rest apparently consisting of lacustrine silt and other ice marginal deposits.

<u>Comparison with nearby organics</u> -- Younger organic deposits are reported from four closely spaced wells west of Kalkaska (Winters et al., 1986), at altitudes 75 m

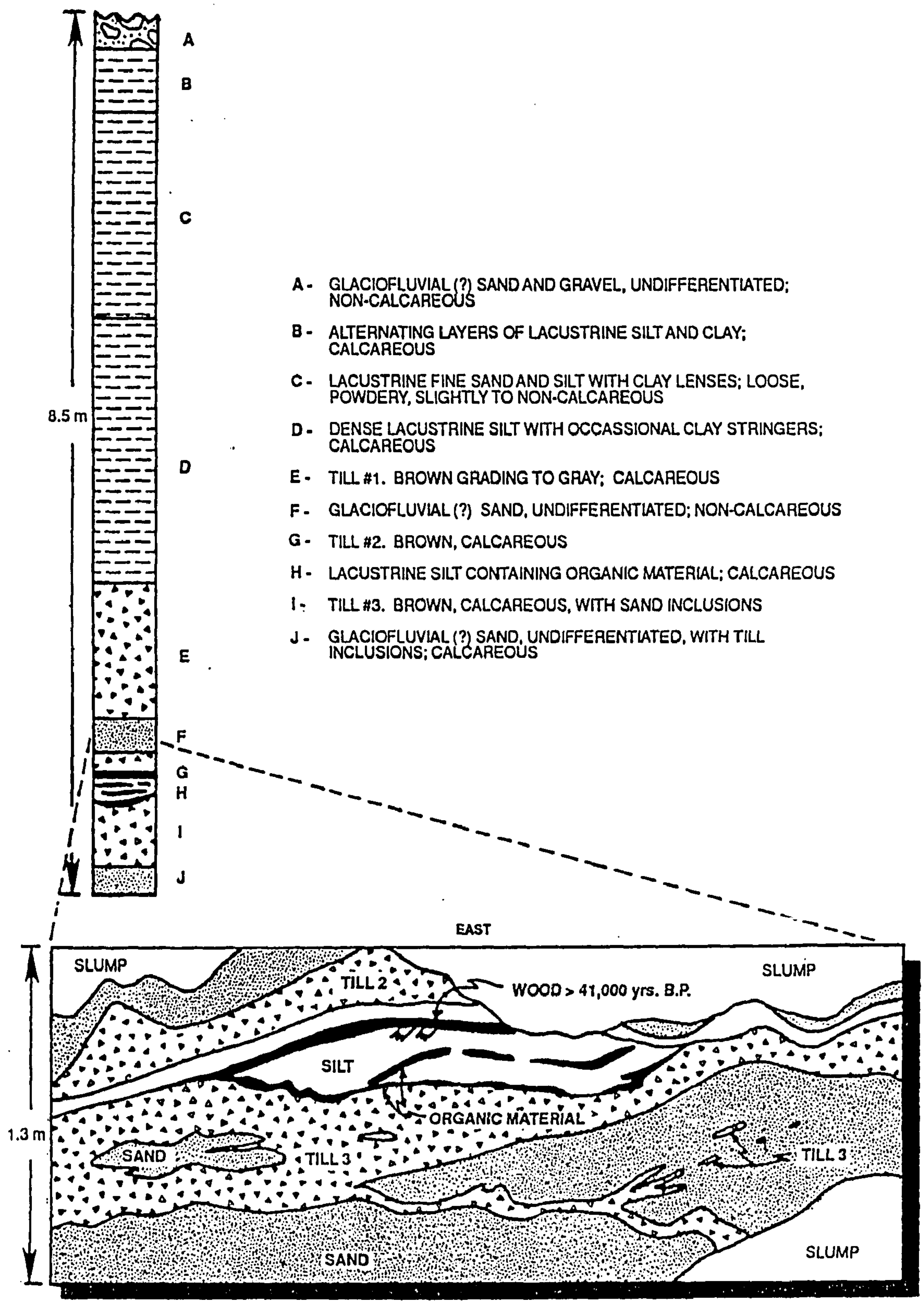

Figure 14 . Rugg Pond Stratigraphy.

lower than the Rugg Pond site. Radiocarbon dates and botanical data indicate that about 35,000 B.P. the area was ice-free, poorly drained, and supported first an open and later a closed boreal forest. If the Rugg Pond organic horizon is at or near its original altitude, then Middle Wisconsinan paleorelief was at least 75 m. This is so because organic deposits, if not transported significantly, record approximate altitudes of buried paleosurfaces. Thus, if organics >41,000 yrs. old are found in situ at 255 m, the same site had to be as high or higher at 35,000 yrs. B.P. Curiously, modern surfaces at these two locations are within 10 m altitude of one another. This is further evidence that present topography here is not palimpsest, and that Late Wisconsinan glaciation has both transformed the topography and subdued the relief.

Surficial sediments

Surficial sediment in the study area is predominantly glaciofluvial sand and gravel; till is almost wholly restricted to fluted uplands and the Post Inner Port Huron zone (Fig. 15). Lacustrine deposits are common in areas immediately up-ice from the Inner and Outer Port Huron features and in association with proximal outwash facies. Details of each are described below.

Sedimentological investigation of nine gravel pits on the Mancelona Plain's most extensive surface (Elmira surface; Ch. 3) constituted a major portion of this study. Samples were taken vertically at each pit and separated into coarse ($>$8 mm) and fine ($<$ 8 mm) fractions. Lithology, roundness and principal axes values were determined for 75 randomly selected coarse ($>$8 mm) fragments. Sphericity and flatness were calculated from axis data; fine fractions were sieved at phi intervals of one unit. Bedform lithofacies, paleodischarges, and paleocurrent directions also were determined.

Discarded stones recovered during potato harvesting are piled along roads north of Alba. Some aspects of localized facies were interpreted by sampling five such stone piles within a 15 mi^2. area. Lithology, roundness, and principal axes were determined for 50 randomly-sampled stones from each pile.

Places where three or more surficial boulders (b-diameter $\geq$50 cm) exist within 100 - 150 m of one another were mapped (Fig. 15), as were locations of single boulders $\geq$1 m. These data were useful in 1) recognizing facies changes in surficial sediments, and 2) determining successive ice marginal positions.

SURFICIAL SEDIMENTS OF THE INNER PORT HURON COMPLEX

The overall statistical distribution of sediment sizes from nine gravel pits on the Elmira surface is shown in Fig 16. Finer textures consist

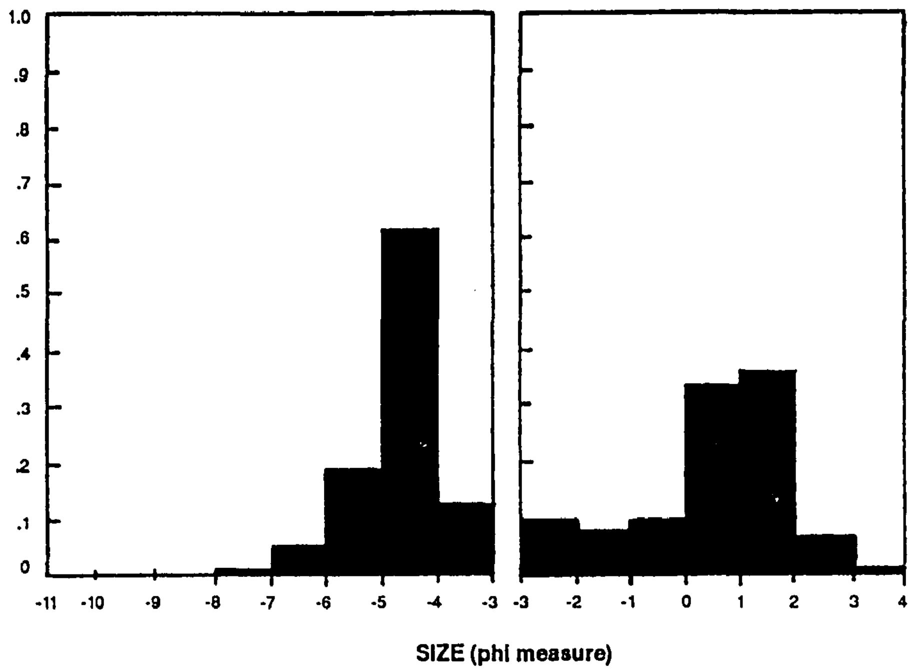

Figure 16. Overall distribution of coarse and fine sediments.

predominantly of medium and coarse sands. Mean b-axis diameter of the coarse fraction is 2.8 cm, with a variance and standard deviation of 3.8 and 1.9 cm, respectively. Kurtosis for the overall population is relatively high (13.2; highly leptokurtic), probably due to an abundance of especially well sorted mid-sandur samples in the population. The distribution is positively skewed, indicating the presence of a few large clasts in proximal locations. Lithologically, coarse clasts in the overall population are 60% carbonate, 25% non-carbonate sedimentary, and 15% crystalline.

Roundness, flatness, and sphericity are shown in Figure 17. Greater roundness reflects more abrasion, whereas flatness and sphericity are terms that describe the shape of a rock. Most large clasts in this study are rounded to sub-rounded and relatively compact, typical of sandur characteristics reported elsewhere (Church, 1972).

<u>Comparison of sediment characteristics among gravel pits</u> -- Mean b-axis values are greatest in proximal gravel pits (Crego and C-K pits; Fig. 18) and smallest at the most distal site (DNR pit; Fig. 18). Analysis of variance (ANOVA) indicates that collectively the nine distributions are statistically different at 99% confidence levels. Because the Crego and DNR sites mark the most proximal and distal gravel pits, respectively, it was reasoned that their sediment distributions should not be the same. The t-test was then applied and the two

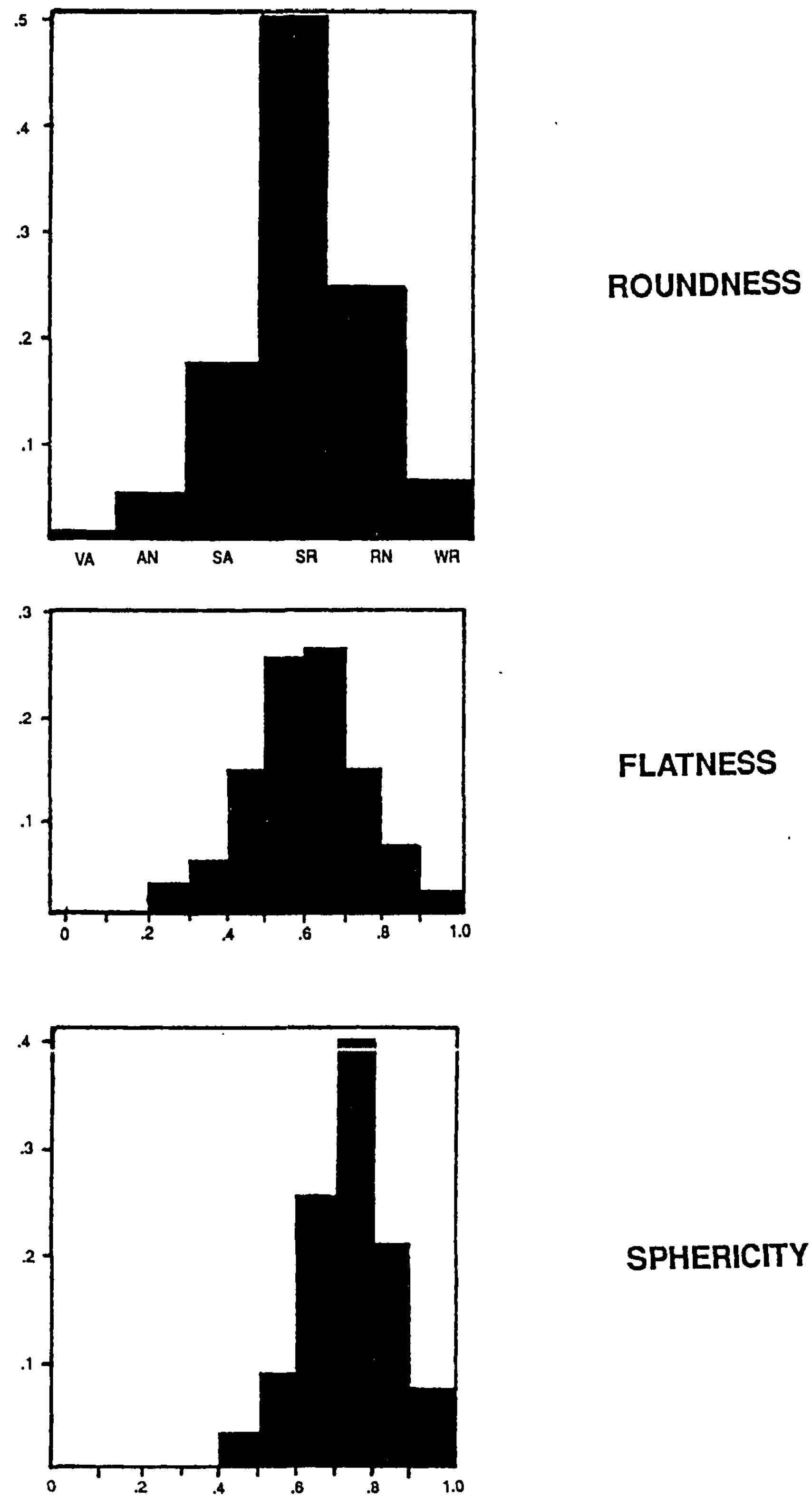

Figure 17. Roundness, flatness, and sphericity of coarse clasts from gravel pits on the Elmira surface.

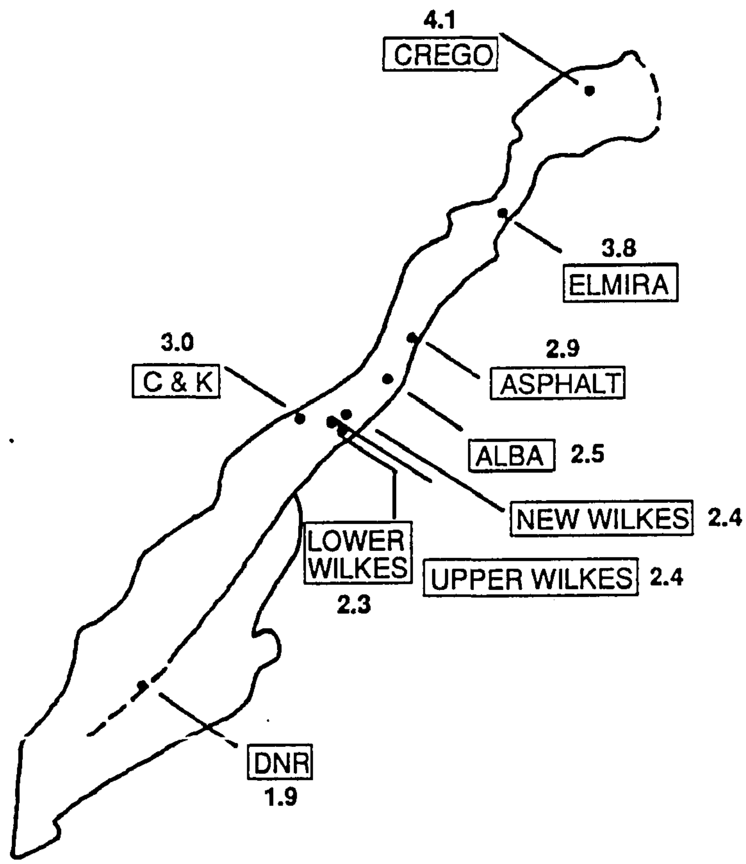

Figure 18. Mean B-axis diameter of coarse clasts from gravel pits on the Elmira surface.

sites were found to be statistically different at 99% confidence values.

Sphericity (Fig. 19) can range from near zero (long, narrow clasts) to one (clasts with equal a,b, and c axes). Visually, higher values appear to be associated with the distal portions of the sandur, but analysis of variance indicates that differences in variability are not statistically significant.

B-axis variance (Fig. 20) measures relative sorting and, in theory, populations near the ice margin would be expected to yield higher values representing poorly sorted conditions. This is substantiated by data from the Elmira surface.

Theoretically, gravel should become more rounded distally, due to greater abrasion from longer transport. No discernible visual difference in gravel roundness was recorded across the sandur, except that rocks classified as "very angular" were restricted to 4 proximal pits (Fig. 21). Thus, except for a small percentage deposited at the glacial margin, nearly all large clasts on the sandur have undergone considerable abrasion, although the amount directly related to transport on the Elmira sandur alone cannot be determined.

Characteristics of finer sediments are shown in Figure 22. Proximal gravel pits contain a higher coarse/medium sand ratio than distal pits. Selected proximal and distal distributions are statistically

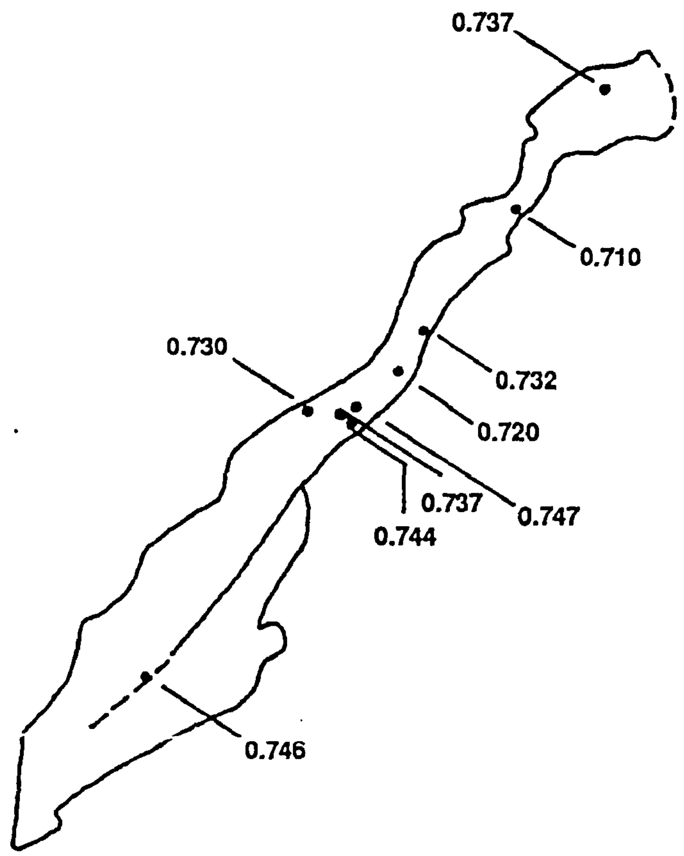

Figure 19. Mean sphericity of coarse clasts from gravel pits on the Elmira surface.

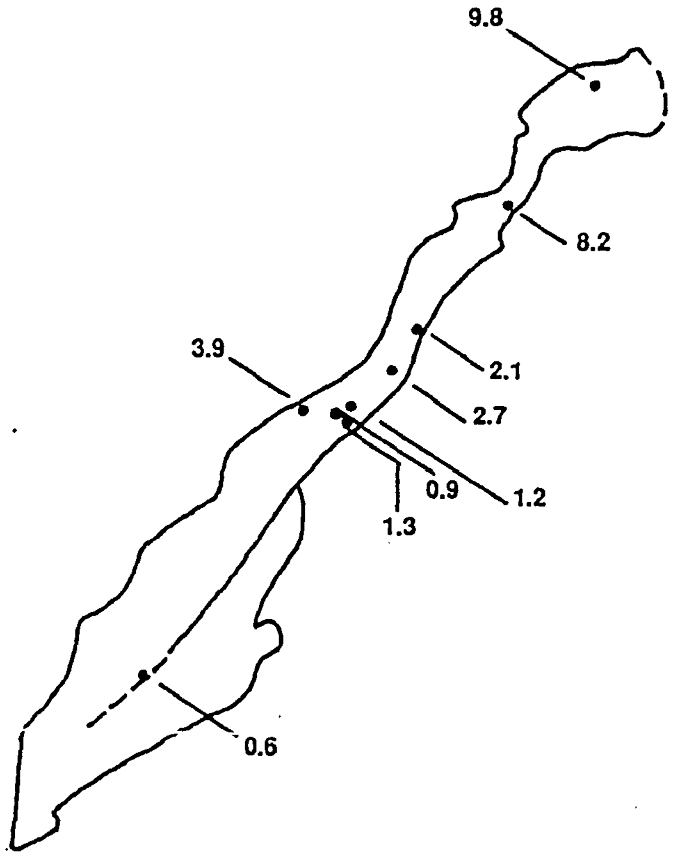

Figure 20. B-axis variance of coarse clasts from gravel pits on the Elmira surface.

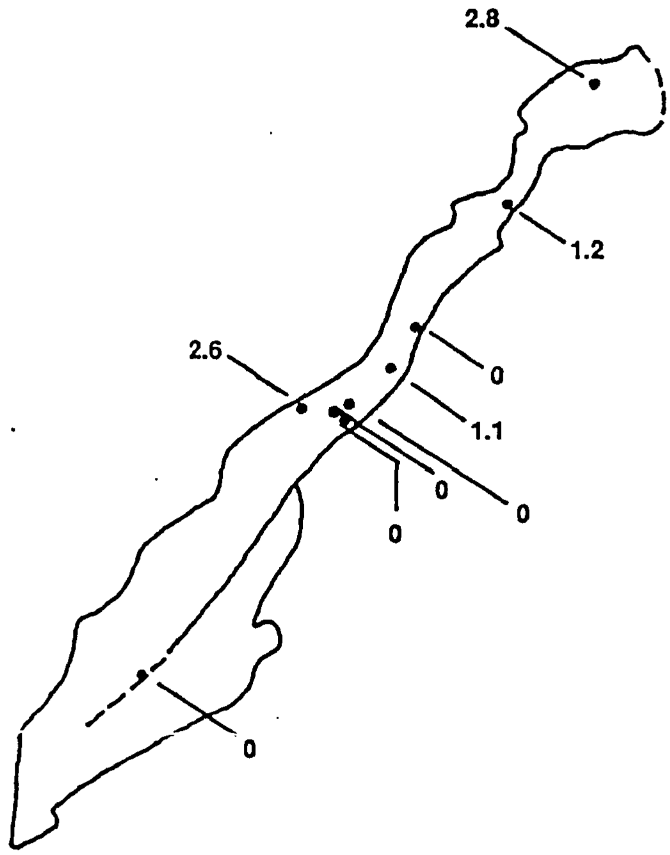

Figure 21. Distribution of "very angular" coarse clasts from gravel pits on the Elmira surface.

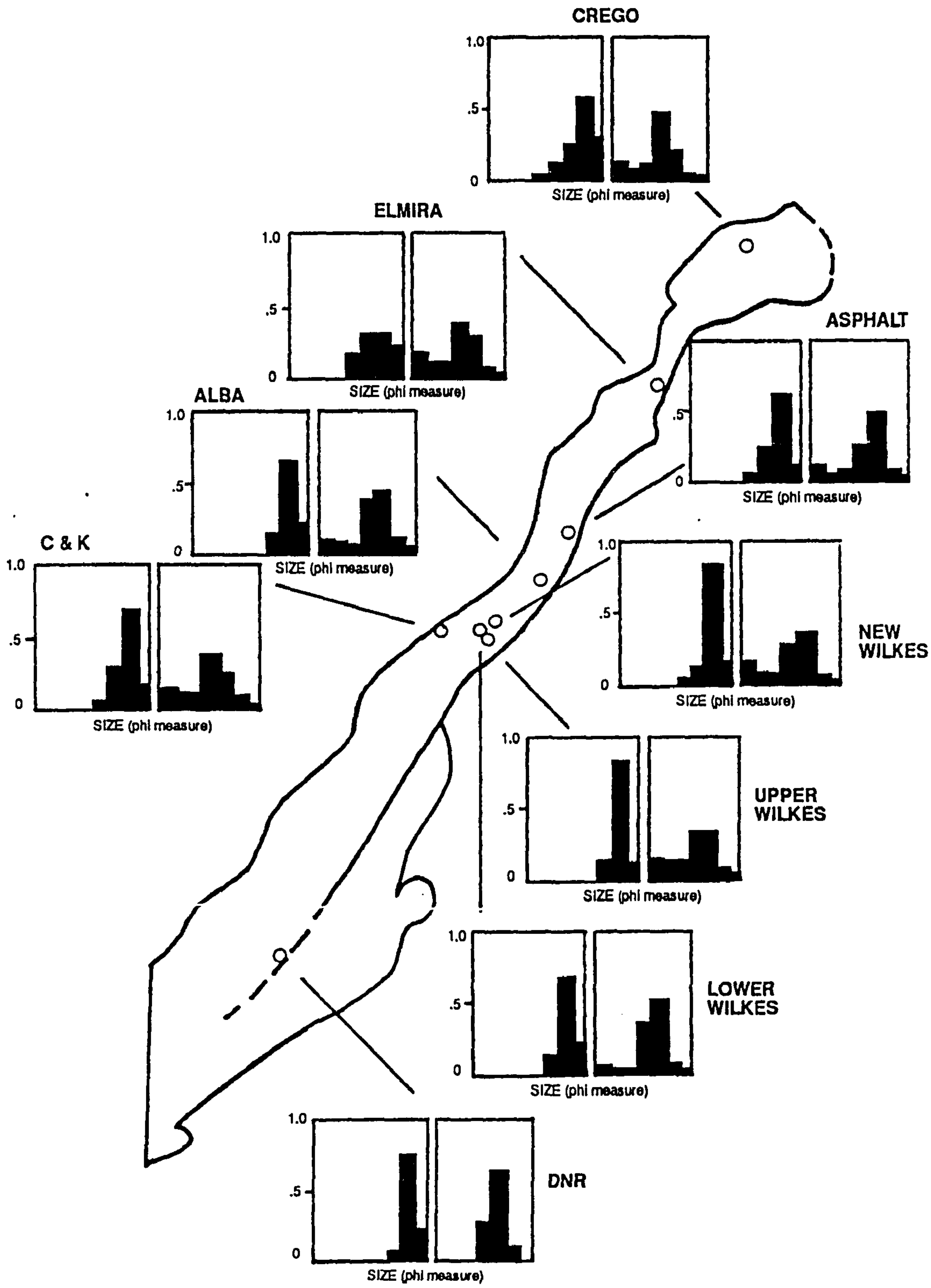

Figure 22. Distribution of coarse and fine sediments from gravel pits on the Elmira surface.

different at 99% confidence values, based on the Kruskal-Wallis analysis of variance.

In short, on the basis of gravel pit data, both coarse and fine fractions exhibit a statistically significant variation in facies. Proximal locations show higher variability in texture and contain larger, more angular, and less compact rocks, whereas distal sites are better sorted and contain smaller, rounder, more compact sediments.

Stonepiles -- Five stonepiles containing pebble and cobble-sized clasts were sampled in order to investigate localized facies changes on the Elmira surface north of Alba. A statistically significant distal fining is identified (Fig. 23). Angular and subangular clasts are located only in proximal locations. A weak tendency exists for more compact clasts to be found distally, but this pattern is not statistically significant. These findings support gravel pit data and suggest that a distally fining facies change exists on the Elmira surface.

Bedforms -- Bedform analysis was used for verifying facies changes in glaciofluvial material. The technique has been described in detail (Miall, 1978; 1983) and consists of identification, description, and interpretation of suites of diagnostic lithofacies units (Miall, 1978). Principal units recognized in this study

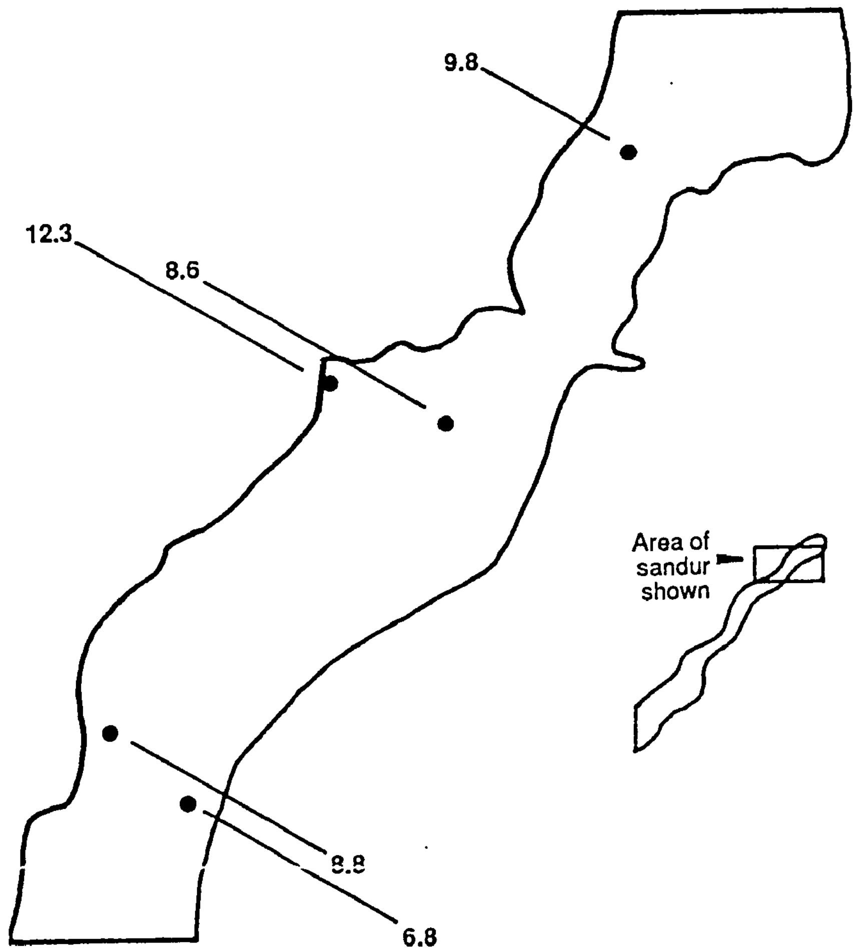

Figure 23. Mean B-axis diameter (cm) of stone piles on the Elmira surface.

are shown in Table 1.

Miall (1983) presented three outwash facies models representing proximal, medial, and distal lithofacies assemblages. Though superseded by a new method called architectural element analysis (Miall, 1985), the facies model approach was utilized in this study because it 1) is relatively simple to use, 2) provides well-established models for comparison, and 3) requires less extensive exposures than architectural element analysis. The principal models include:

> 1) Scott type - Proximal lithofacies dominated by multistorey gravel units deposited by aggradation of longitudinal bars.
>
> 2) Donjek type - Medial lithofacies containing both bar gravels and sands and pebbly sands; sometimes strongly cyclic.
>
> 3) Platte type - Distal lithofacies characterized by low relief bars and channels. Main sediment types are massive, laminated and ripple cross-laminated sandy silts.

An alternate distal facies type named "Bijou Creek" (Miall, 1981) is dominated by lithofacies Sh (planar sands) and represents braided streams characterized by flash floods.

Sediments from each gravel pit on the Elmira surface were carefully documented in the field and photographed. Representative vertical profiles (Fig. 24) were constructed for each site as a means for graphic presentation. Size of outcrops varied widely, and the Alba gravel pit was not included due to poor exposure.

Once identified, lithofacies assemblages were

Table 1. Lithofacies and sedimentary structures of fluvial deposits (from Miall, 1978).

Facies Code	Lithofacies	Sedimentary structures	Interpretation
Gms	massive, matrix supported gravel	none	debris flow deposits
Gm	massive or crudely bedded gravel	horizontal bedding, imbrication	longitudinal bars, lag deposits, sieve deposits
Gt	gravel, stratified	trough crossbeds	minor channel fills
Gp	gravel, stratified	planar crossbeds	linguoid bars or deltaic growths from older bar remnants
St	sand, medium to v. coarse, may be pebbly	solitary (theta) or grouped (pi) trough crossbeds	dunes (lower flow regime)
Sp	sand, medium to v. coarse, may be pebbly	solitary (alpha) or grouped (omikron) planar crossbeds	linguoid, transverse bars, sand waves (lower flow regime)
Sr	sand, very fine to coarse	ripple marks of all types	ripples (lower flow regime)
Sh	sand, very fine to very coarse, may be pebbly	horizontal lamination, parting or streaming lineation	planar bed flow (l. and u. flow regime)
Sl	sand, fine	low angle (<10°) crossbeds	scour fills, crevasse splays, antidunes
Se	erosional scours with intraclasts	crude crossbedding	scour fills
Fcf	mud	massive, with freshwater molluscs	backswamp pond deposits
Fm	mud, silt	massive, desiccation cracks	overbank or drape deposits

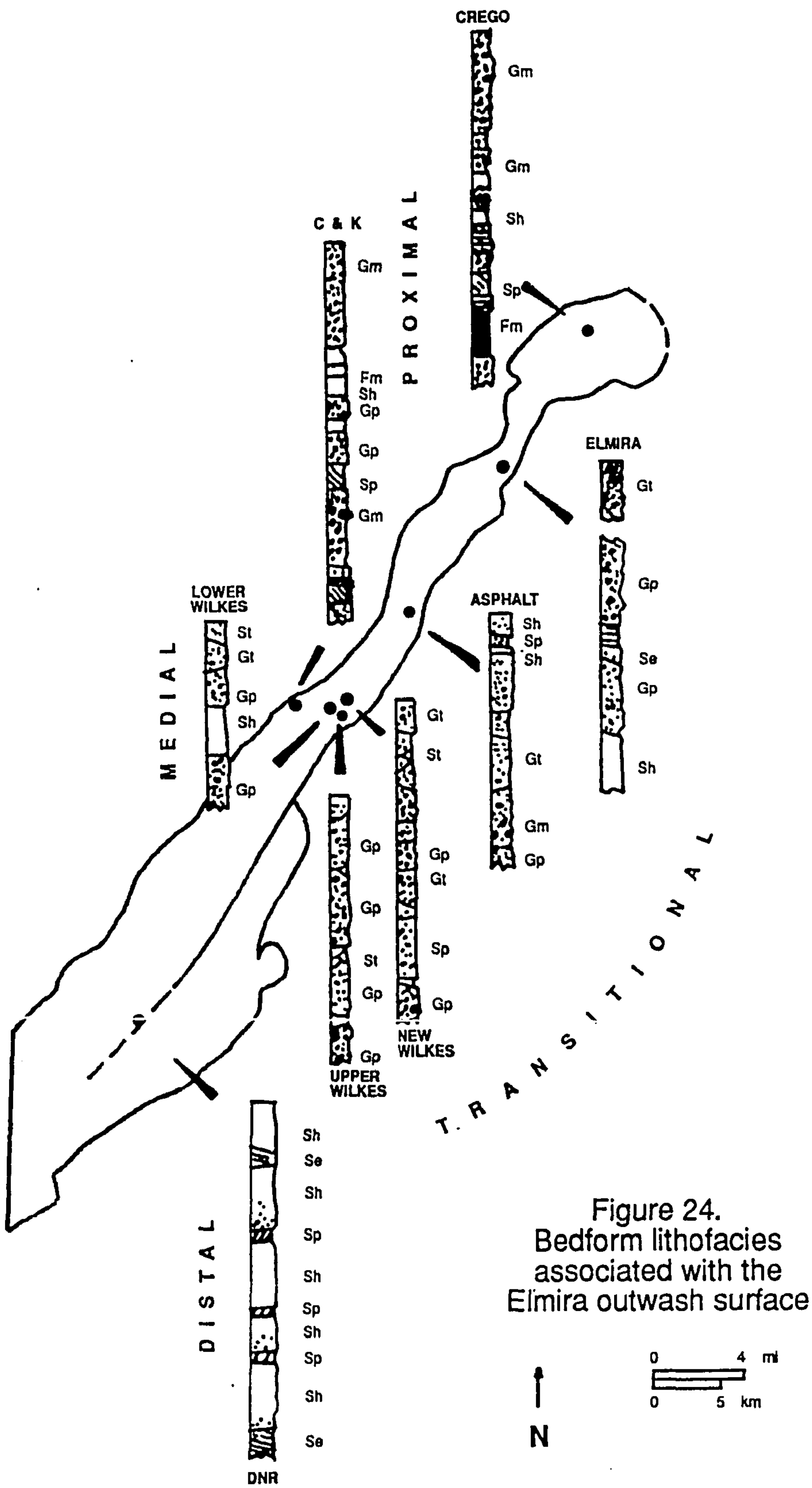

Figure 24.
Bedform lithofacies
associated with the
Elmira outwash surface

classified as proximal, medial, distal, or transitional types (Fig. 24, Table 2) and compared with the Scott, Donjek, Platte, and Bijou Creek models. Principal facies recognized in the present study are identified below:

PROXIMAL: (Crego and C-K gravel pits) This assemblage is dominated by Gm and Gp lithofacies (Fig. 25) but contains moderate amounts of interlayered sand. Gravels are coarse textured, poorly sorted, and include large boulders. A flow till mass is within the Gm facies at the C-K pit, suggesting transition from an ice-contact depositional facies. The Crego site contains lacustrine silt up to 33 cm thick, and clay drapes are identified in both gravel pits.

MEDIAL: (Lower Wilkes pit) This site is dominated by Gp and St lithofacies (Fig. 26), and includes cyclical aggrading sandy bedforms and broad scour fills. Sediments are 1) finer grained, 2) better sorted, and 3) cross-stratified to a much greater degree than proximal pits. There is a higher proportion of sand to gravel and the latter is finer grained. Cobbles are rare. No silt or clay drapes are identified.

TRANSITIONAL: (Elmira, Asphalt, Upper Wilkes, and New Wilkes gravel pits) Facies at these pits are characteristic of both medial and proximal sites. Gravels are smaller and somewhat better sorted than those in proximal pits. They also exhibit a greater abundance of planar (Gp) and trough-cross bedding (Gt), rather than

TABLE 2. Bedform lithofacies of gravel pits on the Elmira surface.

Site	Facies identified	Designation	Comments
Crego	Gm, Gp, Gt, Sh, Sp, Fsc	Proximal	Gm and Gp predominate; thick, lacustrine sandy silt
Elmira	Gm, Gp, St	Transitional	Gm and Gp predominate; no silt
Asphalt	Gm, Gt, Gp, St, Sh, Sp	Transitional	Gm, Gt, St predominate; no silt; more sand than Crego, Elmira
C and K	Gm, Gp, Gt, Sh, St, Fm, Fsc, Gms	Proximal	Gm predominates; silt, clay drapes; small flow till inclusion in Gm
Lower Wilkes	Gp, St, Sp, Sh	Medial	Gp, St predominate; no silt
Upper Wilkes	Gt, St, Gp, Sp, Sh	Transitional	Gp predominates; no silt
New Wilkes	Gt, Gp, Sp, St	Transitional	No silt
DNR	Sh, Sp, St,	Distal	Thick, fining upward Sh

Figure 25. Sediments at the C and K gravel pit (proximal), Mancelona.

Figure 26. Sandy bedforms at the Lower Wilkes gravel pit (medial), Mancelona.

massive gravel sheets (Gm).

DISTAL: (DNR gravel pit) Sediments here are composed almost exclusively of sand and granules. Lithofacies Sh dominates the pit (Fig. 27). Large scour fills, but no silt or clay layers, are recognized.

INTERPRETATION AND COMPARISON -- Proximal gravel pits contain more sandy bedforms than predicted by the Scott facies model but otherwise exhibit many characteristics of proximal facies. These include 1) the presence of boulders and overall coarse texture, 2) dominance of Gm facies, 3) presence of thick (38 cm), cross-bedded gravel (Gp) lenses, indicative of high energy, deep water deposition and, 4) presence of silt lenses and clay drapes, possibly representing overbank sediments deposited during waning flood stages.

In general, the Gm facies represents deposition of gravel sheets and longitudinal bars during rapid deposition of bedload from transport during waning flood stages (Miall, 1981). Clay drapes and sand and silt lenses indicate that flow conditions were highly variable, typical of proximal outwash environments (Church, 1972; Fraser and Cobb, 1982).

The medial bedform facies at the Lower Wilkes site is similar to the Donjek model, except for the absence of silt at the Lower Wilkes gravel pit. These sediments represent a variety of bars and bedforms typical for a wide, shallow, braided stream (Fraser and Cobb, 1982).

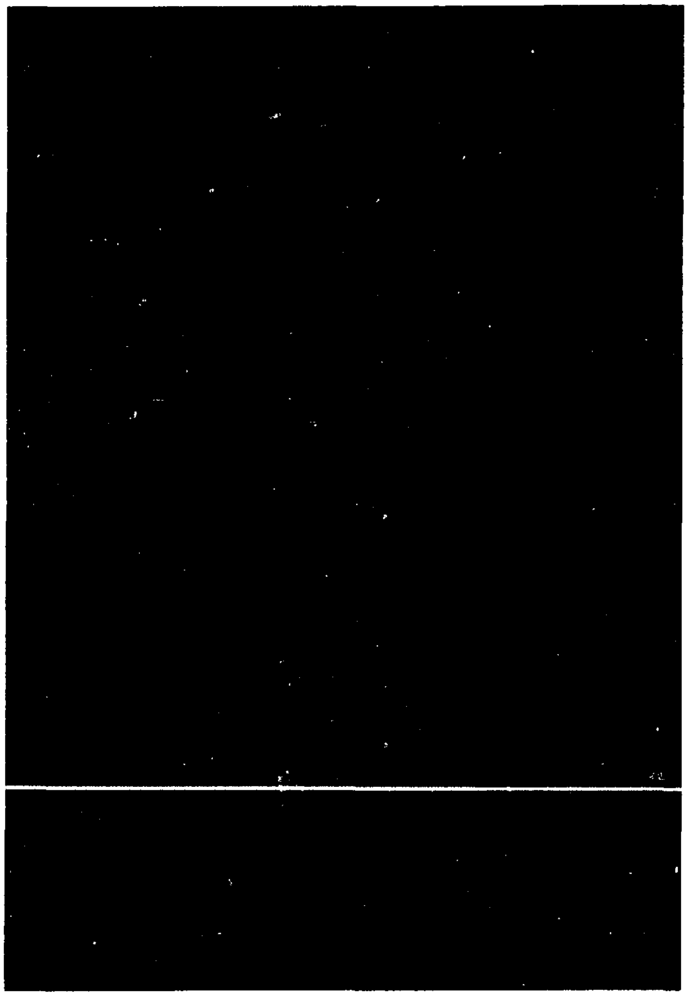

Figure 27. Lithofacies Sh at the DNR sand pit (distal), Kalkaska.

The distal DNR gravel pit has characteristics of both the Platte and Bijou Creek models. In places, thick sequences of planar sands (Sh) are capped by thin planar cross-bedded layers (Sp). A fining upward is indicated by pebbles at the bottom of some Sh units. On these bases, the deposits are interpreted as a braided stream system exhibiting markedly variable discharge with periodic flooding (Bijou Creek model). Elsewhere in the exposure, areas of broad scour fills are identified, more typical of the Platte facies model. Areas of the pit where key relationships might be established are not exposed. A parsimonious approach identifies this site as a distal facies, with details of interpretations awaiting further study.

In summary, analysis indicates that a definite change in bedform facies exists in Elmira outwash deposits. These facies range from coarse, poorly sorted, proximal meltwater deposits dominated by longitudinal bars to distal fine textured, well-sorted, braided stream deposits dominated by sandy bedforms. This change in bedform facies complements textural analysis and supports the interpretation that what was previously mapped as the Inner Port Huron Moraine crest actually marks an especially important head of outwash, which is graded to the extensive Elmira surface of the Mancelona Plain.

Paleocurrents -- Paleocurrent directions were recorded at eight gravel pits and consisted of 1) measurement of imbricated gravel fabrics (Rust, 1975), and 2) determination of dip direction within planar cross-bedded sands, based on stereographic plots of apparent dip and strike. Paleocurrent directions are perpendicular to the ice margin in proximal regions and parallel to the ice margin along the axis of the sandur (Fig. 28). These data indicate that meltwater first tended to flow perpendicularly away from the ice margin, to then turn 90 degrees right to run parallel to the margin in the sandur's distal tracts. Fraser and Cobb (1982) found similar current patterns in valley trains paralleling the West Chicago Moraine in Illinois.

Paleodischarge -- Paleodischarge estimates were calculated to determine whether or not catastrophic drainage occurred. Assumptions and difficulties of paleodischarge analysis have been reviewed in detail (Briggs, 1983; Maizels, 1983a; Lord and Kehew, 1988). All methods depend on direct or surrogate measurements for use in the equation $Q = w * d * v$, where Q = discharge, w = channel width, d = mean channel depth, and v = mean channel velocity. Paleodischarges were determined for the Elmira surface overall and for representative proximal and medial gravel pits. These values most likely are greatly underestimated due to the difficulty in determining accurate channel widths. Where

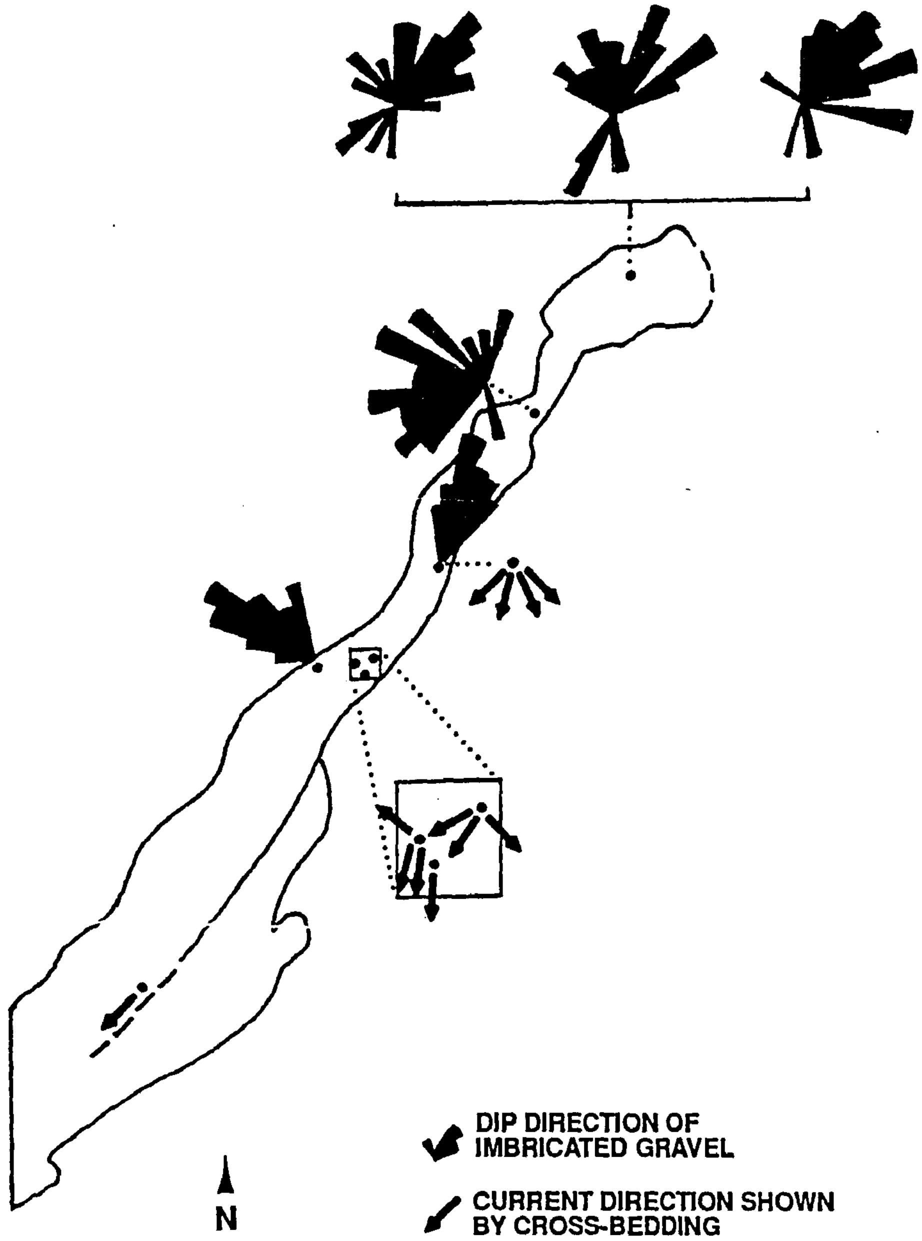

Figure 28. Paleocurrents on the Elmira surface.

applicable, slopes were adjusted for isostatic rebound of approximately 20% and for an assumed sinuosity of 1.1 for braided streams. Methods used in this study are discussed briefly below.

Slope - discharge methods

Leopold and Wolman (1957) demonstrated that, at a constant discharge, braided streams have steeper slopes than those that meander, and that the boundary between the two was approximated by the equation:

$$S = 0.06 * Q^{-0.44}$$

where S = tangential slope.

Although some braided streams exist outside of this predicted range, the equation provides a method for determining minimum bankfull discharges of braided systems on a given slope.

Cheetham (1976, 1978) calculated the regression equation for Leopold and Wolman's braided streams and derived the following relationship:

$$Qbf = 0.000585 * S^{-2.01}$$

where Qbf = bankfull discharge. Both equations are minimum estimates only and assume no overbank flow.

Briggs method #2

Briggs (1983) presents several methods for determining paleodischarge. His second method requires only channel slope, particle diameter (D_{84}), and estimates of percent silt and clay in the channel perimeter. Velocity is determined from Sundborg's diagram. Depth is calculated using the Manning equation:

$$D = \left(\frac{V * n}{\sqrt{S}} \right)^{1.67}$$

where n = Manning roughness, V = velocity, and D = depth. Manning roughness is determined using Strickler's formula:

$$n = 0.0132\ D_{84}^{0.17}$$

Channel width is calculated using Schumm's expression:

$$W = (255 * M^{-1.08})\ D$$

where W = width and M = % silt and clay in the channel perimeter. Estimates of depth, velocity, and width are then combined in the expression Q = W * V * D to calculate discharge.

· Maizels methods #1 and #2

Maizels (1983a) presents a thorough review of paleodischarge techniques, including a number of simplified equations requiring inputs of only particle diameter and slope. Unfortunately these equations give estimates for critical specific discharge (qc), which must be multiplied by channel width to provide total critical discharge (Qc). Except for the Lower Wilkes pit, where a conservative estimate of channel width was possible, widths were derived using Schumm's expression described above. Derivation of the following equations are discussed in Maizels (1983a):

Maizels method #1 (Chezy equation)

$$qc = \frac{5.52\ D^{3/2}}{S^{2/3}}$$

Maizels method #2 (Manning - Strickler equation)

$$qc = \frac{0.29^{3/2}\ [1.16 + 2\log\left(\frac{0.1029}{s}\right)]}{S}$$

where qc = critical specific discharge, D = clast size (D_{84} in this study), and s = channel slope.

Except for Leopold and Wolman's technique, estimates from the Elmira surface are generally in agreement, ranging from 415 - 915 $m^3\ sec^{-1}$ (Table 3). Likewise, paleodischarges for the Lower Wilkes pit are comparable if widths from Schumm's relationship are used. Wide discrepencies occur in Crego values, probably due to width estimates that are much too large (322 m).

Even so, these data tend to confirm texture and bedform analysis, suggesting that the sediments observed were not deposited in association with catastrophic drainage. These values are also comparable to paleodischarges from other formerally glaciated regions, including Scotland (1040 - 3120 $m^3\ sec^{-1}$; Maizels, 1982) and the Canadian Rockies (1000 - 6000 $m^3\ sec^{-1}$; Clague, 1975).

TABLE 3. PALEODISCHARGE ESTIMATES.

Site	Leopold and Wolman	Cheetham	Briggs #2	Maizel #1	Maizel #2
Elmira surface overall	Q=10,600 $m^3\ sec^{-1}$	Qbf=610 $m^3\ sec^{-1}$	Qb=415 $m^3\ sec^{-1}$	qc=2.8 Qc=429 $m^3\ sec^{-1}$	qc=6.1 Qc=915 $m^3\ sec^{-1}$
Crego	Q=695 $m^3\ sec^{-1}$	Qbf=55 $m^3\ sec^{-1}$	Qb=2450 $m^3\ sec^{-1}$*	qc=8.7 Qc=2800 $m^3\ sec^{-1}$*	qc=12.6 Qc=32 $m^3\ sec^{-1}$*
Lower Wilkes	Q=210 $m^3\ sec^{-1}$	Qbf=19 $m^3\ sec^{-1}$	Qb=30 $m^3\ sec^{-1}$	qc=.6 Qc=30 $m^3\ sec^{-1}$*; Qc=6.1 $m^3\ sec^{-1}$	qc=.6 Qc=32 $m^3\ sec^{-1}$*; Qc=6.5 $m^3\ sec^{-1}$

*using width from Schumm's expression

<u>Till associated with the Inner Port Huron Complex</u> -- Pink till (5 YR 7/3, dry) crops out in scattered locations along the Inner Port Huron apex (Woodland and Crego tills, Table 5), and is best exposed at Crego's northernmost gravel pit (NE1/4, NW1/4, SW1/4, sec. 15, T. 32 N., R. 4 W.). Characteristics of this till include:

1) Juxtaposition of till and glaciofluvial sand and gravel.

2) Contorted glaciofluvial bedding sloping toward deep closed depressions immediately adjacent to the exposure.

3) Presence of boulders at the top of the exposure, possibly suggesting dumping of materials from adjacent stagnant ice.

4) Vertical contacts between till and glaciofluvial sediments; dragfolding indicates till moved downward relative to stratifed layers.

Keeble (1970) and Shaw (1972) attributed similar assemblages to deposition of superglacial till and meltwater sediments into moulins or crevasses. Evidence at the Crego site indicates that till here was deposited in a similar fashion.

SEDIMENTS ASSOCIATED WITH THE POST INNER PORT HURON ZONE

The Post Inner Port Huron zone is located just proximal to the Inner Port Huron ice-contact slope. Sediments are predominantly glaciofluvial sand and gravel, with lesser amounts of till and lacustrine silt and clay.

Few exposures of glaciofluvial deposits were located.

A small exposure in outwash surface A (Ch. 3, NE1/4, SE1/4, T. 31 N., R. 5 W.) exhibits stratified sand and gravel with well-sorted, rounded cobbles up to 10 cm in b-diameter.

The Antrim County Road Commission gravel pit (NW 1/4, NW 1/4, sec. 33, T. 30 N., R. 6 W.) contains complexly folded lacustrine silt/clay layers (Fig. 29) with overlying unconformable, undeformed outwash sand and gravel (not shown in diagram). Organic matter recovered from a distinctive layer of this lacustrine clay yielded a radiocarbon date of 12,960 ± 350 yrs. B.P. (TX - 6151). Samples were taken from the lower part of a small yet obvious anticline 2 m below the top of the exposure along the east bank of the pit (Fig. 29). Based on the radiocarbon date and an analysis of stratigraphy, three principal successive events are recognized:

1) Lacustrine and organic matter deposition c. 12,960 yrs. B.P.

2) Deformation of lacustrine deposits.

3) Initiation of fosse meltwater drainage, and deposition of outwash sediments.

Interpretation and significance of this stratigraphy is discussed in Chapter 4.

Two main till exposures were identified in the Post Inner Port Huron zone.

Plum Valley site: (SE1/4, SW1/4, sec. 6, T. 28 N., R. 7 W.) This site contains two tills: 1) a brown (10 YR 7/3, dry) basal till at an altitude about 66 m below the

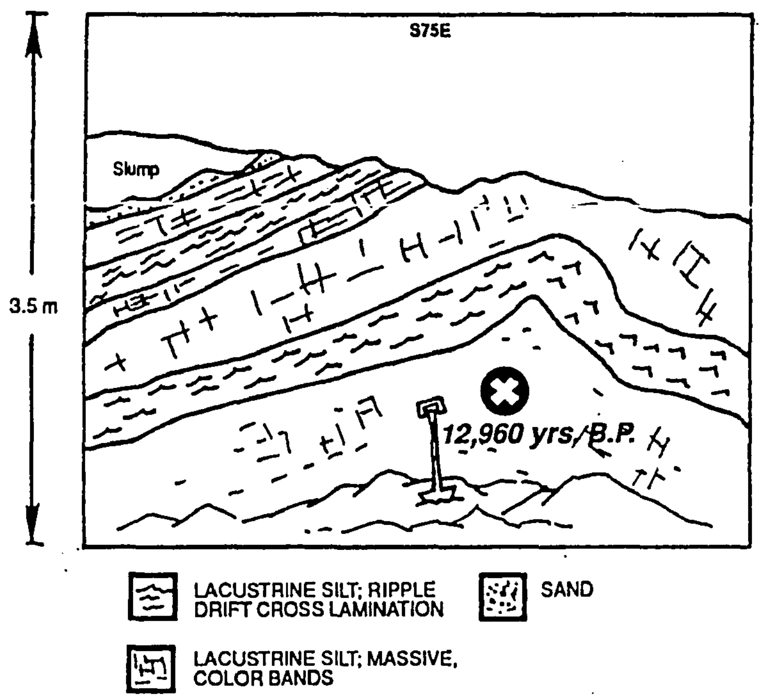

Figure 29. Stratigraphy at the Antrim County Road Commission gravel pit.

crest of the Inner Port Huron ice-contact slope, and 2) an overlying deposit containing alternating layers of sandy stratified till and sand lenses. In places, the two tills are separated by planar sands up to 35 cm thick.

Flow till has been recognized and described by, among others, Hartshorn (1958), Kaye (1960), Boulton (1968, 1971, and 1972), and Rieck (1976). Collectively, these studies recognize nine criteria for identifying flow till:

1) Interfingering of the flow till unit with glaciofluvial sediments.

2) Orientation of striated pebbles parallel to the direction of movement.

3) Presence of sandy lenses and horizons incorporated within the deposit.

4) Sharp planar contact with subadjacent materials.

5) Smooth, vertical faces in relatively fresh exposures.

6) Overconsolidated nature when dry.

7) Close association with ice-contact slopes.

8) Presence in higher topographic positions within the landscape.

9) Till fabrics parallel to maximum surface slopes.

The upper till exhibits interfingering, pebble orientation, and sandy lenses. Sharp planar contacts also exist between this till and the planar sands mentioned above, but smooth overconsolidated facies are absent. The deposit caps a small ridge 1/2 mile proximal to the Inner Port Huron ice-contact slope, satisfying criteria #7 and #8. On all these bases, the upper till is identified as flow till.

Because of the limited data available, the age of these deposits is difficult to determine. The lower till may represent subglacial deposition during advance to the Outer Port Huron position, with subsequent flow till deposition during deglaciation.

Simpson gravel pit: (SE1/4, NE1/4, sec. 11, T. 29 N., R. 7 W.) Here, a sandy till exposed in a northwest-southeast trending disintegration ridge displays the following characteristics: 1) interfingering with glaciofluvial sediments, 2) orientation of striated pebbles, 3) presence of sandy lenses and horizons, 4) high topographic position and 5) close association with the Inner Port Huron ice-contact slope. On these bases it is interpreted as flow till.

TILLS ASSOCIATED WITH FLUTED UPLANDS

Till is widespread in fluted uplands proximal to the Post Inner Port Huron zone; four exposures were examined in detail:

1) Barker Creek (NW1/4,SE1/4, sec. 31, T. 28 N., R. 8 W.)

2) Torch Lake (SE1/4,NE1/4, sec. 33, T. 29 N., R. 8 W.)

3) Zimmerman Road (SE1/4,NE1/4, sec. 4, T. 28 N., R. 8 W.)

4) Thumb Lake Road (SE1/4,SE1/4, sec. 12, T. 32 N., R. 5 W.)

With the exception of #4, all are brown in color (10 YR

6/3, 7/3, dry; Table 5) and located south and east of Skegemog and Torch Lakes. Melhorn (1956) identified pink (5 YR 7/3, dry) Thumb Lake till as "Valders till." No consistent stratigraphic relationships among the tills are recognized in this study. Texture, color, and clay mineralogy are discussed later in this chapter.

SURFICIAL SEDIMENTS ASSOCIATED WITH THE OUTER PORT HURON COMPLEX

Only two large exposures (Fleming and Rosenburg Rd. gravel pits) existed within the Outer Port Huron feature at the time field study was conducted. Deposits are mostly glaciofluvial sand and gravel, with some glaciolacustrine clay in the south and absence of basal till. Principal outcrops are discussed below.

Fleming Farm gravel pit: (NE1/4, NE1/4, sec. 11, T. 31 N., R. 4 W.). Here, a chocolate-brown till (10 YR 6/3) cores a north-south oriented ridge composed of deformed glaciofluvial deposits; these latter sediments display a uniform convex-upward curvature.

The 1) linear nature of the ridge, 2) deformation of glaciofluvial sediments, 3) juxtaposition of till and stratified sediments, and 4) presence of multiple disintegration ridges of similar size and orientation nearby indicate that these sediments were deposited within crevasses in stagnant ice (Kaye, 1960; Keeble, 1970).

Rosenburg Road gravel pit: (SE1/4, NE1/4, sec. 13, T. 27 N., R. 7 W.). This pit is located near the proximal edge of the Outer Port Huron Complex and contains boulders, highly deformed coarse glaciofluvial sand and gravel, and lacustrine silt and clay lenses. A 3 m thick lacustrine clay is exposed at the southern face of the pit. Deformation structures apparently are related to an adjacent closed depression 12 m deep. Shaw (1972) interpreted similar sediments in England as ice-contact stratified drift.

Other Exposures: Excavations for the "Mancelona Water Building" (NE1/4, sec. 21, T. 29 N., R. 6 W.) showed stratified sand and gravel in the Outer Port Huron ice-contact slope, 30 - 40 m below the crest. This outcrop provides additional evidence for the abundance of ice-marginal deposits within the Inner and Outer Port Huron features; thick sand and gravel layers reported from nearby well logs at corresponding altitudes are probably glaciofluvial deposits as well.

Other glaciofluvial outcrops are listed below:

1) SW1/4, NE1/4, sec. 10, T. 30 N., R. 5 W.
2) NW1/4, SW1/4, sec. 11, T. 30 N., R. 5 W.
3) SW1/4, NW1/4, sec. 14, T. 30 N., R. 5 W.
4) SW1/4, SE1/4, sec. 32, T. 28 N., R. 6 W.
5) SE1/4, NW1/4, sec. 17, T. 27 N., R. 6 W.
6) SE1/4, SE1/4, sec. 32, T. 26 N., R. 8 W.
7) E1/2, NW1/4, sec. 15, T. 25 N., R. 8 W.

Thick lacustrine deposits crop out at several places east of Kalkaska. They are best exposed in the NW1/4, NE1/4, sec. 26, T. 27 N., R. 7 W, where a 30 cm thick sand and gravel unit (bedding indistinct) overlies a massive, chocolate brown lacustrine clay more than two meters thick. No banding or lamination of the clay is recognized. These clays apparently were deposited in a proglacial lake that formed between the ice margin and the Outer Port Huron ice-contact slope (Melhorn, 1954).

Melhorn writes (1954; p. 81) "(lacustrine) clays grade vertically, with no noticeable break, into the tough, slightly pebbly blue till below." No similar relation was observed along the Outer Port Huron ice-contact slope in the study area. In fact, only one small exposure of till (Creighton Road till, Table 5) was recorded anywhere south of the Outer Port Huron apex.

<u>Evidence for facies changes in the Outer Port Huron Complex</u> -- Facies changes were determined using 1) boulder distributions (see next section), 2) stone pile mapping, and 3) field examination of outcrops. Initially, piles of stones were located in order to construct a sampling network similar to that on the Elmira surface. These piles are restricted to a very narrow zone along the ice-contact slope, however, and none were found more than 1 kilometer distal to the crest. Fortunately, this pattern is itself significant, and, combined with boulder distributions and field observations, is evidence for a facies change from coarse to fine distally.

<u>Boulder distribution</u> -- Large boulders ($\geq$1.0 m b-diameter) and groups of boulders (3 or more boulders $\geq$ 0.5 m b-diameter within 100-150 m of one another) are

concentrated along narrow zones at the crest of ice-contact slopes marking heads of outwash (Fig. 15). These distributions are believed to result from deposition of superglacial boulders by mass wasting at the ice margin during final deglaciation. Similar boulder concentrations were identified in northern Michigan (Blewett and Rieck, 1987) and used in establishing facies changes, delimiting ice marginal positions, and verifying ice marginal stagnation. In a similar fashion, boulder distribution data presented in this study 1) verify facies changes based on textural analysis of gravel pits and stone piles, 2) help to identify ice marginal positions, and 3) support the stagnation-zone hypothesis for final deglaciation.

An anomalous boulder concentration is located along the base of the Alba East terrace (Ch. 3), proximal to the Outer Port Huron ice-contact slope. It is best observed immediately south of the Alba Airport (SW1/4, NE1/4, sec. 31, T. 30 N., R. 5 W.), where more than 50 crystalline boulders, apparently encountered during road construction, are piled along Arthur Lane. Many other boulders are nearly buried by surrounding glaciofluvial sand and gravel, with only the upper 10-20 cm exposed. Significance of this site is discussed in Chapter 4. Similar concentrations are located in the NW 1/4, NE 1/4, sec. 3, T. 30 N., R. 5 W., and NE 1/4, NW 1/4, sec. 19, T. 31 N., R. 4 W.

SOILS

Soils are a useful means for determining texture and pattern of surficial parent material. Soils in the study area are predominantly sand, sandy loam, and loamy sand in texture (Table 4). Loams, clay loams, and silty clay loams are rare but may be useful indicators of till or lacustrine deposits as demonstrated below:

a. Nester silty clay loam: may delineate Melhorn's Valders till north of the Inner Port Huron apex.

b. Bergland loam; Bergland clay loam: may delimit lacustrine clay in the Outer Port Huron feature.

c. Barker loam: interpreted as brown till in fluted uplands.

d. Chestonia silty clay loam: interpreted as lacustrine (?) deposits in Antrim County.

Soils along the crest of ice marginal positions tend to be finer textured than do more distal soils. This distribution probably reflects an abundance of overbank silt and clay in these proximal deposits, as well as fine sediment deposition within an open gravel matrix during waning flood conditions. Debris flows, ice-contact lacustrine silt and clay, flow and ablation tills, and other fine-textured sediments are also concentrated in proximal regions marking heads of outwash. All these characteristics are typical of areas experiencing ice marginal stagnation, and provide a useful basis for interpreting soil patterns in the study area.

TABLE 4. SOILS OF THE STUDY AREA.

	County	Principal Soil Complexes or Associations	Principal Soil Series	Surface Soil Texture
INNER PORT HURON COMPLEX	Charlevoix	Kalkaska-Leelanau	Kalkaska Leelanau	sand loamy sand
		Leelanau-Emmet	Leelanau Emmet	loamy sand sandy loam
		Mancelona-East Lake	Mancelona East Lake	loamy sand gravelly loamy sand
		Alpena-Kiva-East Lake	Alpena Kiva East Lake	gravelly sandy loam to gravelly sand
	Antrim (proximal)	Kalkaska-Montcalm	Kalkaska Montcalm	sand loamy sand
	Antrim (distal)	Kalkaska-East Lake	Kalkaska East Lake Rubicon	sand gravelly sand sand
	Kalkaska (proximal)	(old survey)	Kalkaska	loamy sand
	Kalkaska (distal)	(old survey)	Rubicon Grayling	sand sand
OUTER PORT HURON COMPLEX	Antrim (proximal)	Kalkaska-Montcalm	Kalkaska Montcalm	sand loamy sand
	Antrim (distal)	Kalkaska-East Lake-Karlin	Kalkaska East Lake Karlin Rubicon	sand gravelly loamy sand loamy fine sand sand
	Kalkaska (proximal)	(old survey)	Emmet	sandy loam
	Kalkaska (distal)	(old survey)	Kalkaska Emmet	sandy loam sand
POST INNER PORT HURON ZONE	Antrim/ Charlevoix	Kalkaska-Montcalm	Kalkaska Montcalm	sand loamy sand
	Kalkaska	(old survey)	Kalkaska Emmet	loamy sand sandy loam

Sources: Veatch et al. (1927); Alfred and Hyde (1974); and Larson and Buchanan (1978).

TEXTURE AND LITHOLOGIC COMPARISON OF TILLS FROM THE STUDY AREA

The variable distribution and relative paucity of till outcrops does not provide an adequate basis for detailed till analysis. Texture, color, and clay mineralogy are, however, presented for descriptive purposes (Table 5). Analysis of large clasts showed no significant lithological differences among the few diamictons sampled. Tills were subdivided on the basis of 1) color (pink vs. brown) and 2) whether they represent the uppermost till in the area (high or low probability).

Texture and correlation of tills - Texture was plotted on a ternary diagram to investigate possible sample groupings (Fig. 30). Red till samples are concentrated in the lower-middle part of the diagram, due in part to the restricted geographic area from which the samples were taken, and are likely from the same deposit. Brown samples separate into two distinct groups containing 1) the Creighton Rd., Barker Creek, and Plum Valley tills, and 2) the Zimmerman, Torch Lake, and Fleming deposits. The Zimmerman and Torch Lake samples were taken less than 1 km apart at similar altitudes (198 and 210 m, respectively) and are probably from the same deposit. This conclusion is supported by color and clay mineralogy data (Table 5). The Plum Valley and Barker Creek samples also display similar texture, but the

TABLE 5. COLOR AND CLAY MINERALOGY OF PRINCIPAL TILLS.

Sample name	#	Munsell moist	color moist	Munsell dry	color dry	7Å*	10Å*	7/10Å	Brown/ Red
Barker Creek	1	10YR 6/3	pale brown	10YR 7/3	very pale brown	61	102	.598	B
	2	10YR 6/3		10YR 7/3		53	83	.638	B
	3	10YR 6/3		10YR 7/3		31	83	.373	B
Woodland #1	4	5YR 5/3	reddish brown	5YR 6/3	light reddish brown	23	20	1.150	R
	5	5YR 5/3		5YR 6/3		26	10	2.600	R
	6	5YR 5/3		5YR 6/3		44	25	1.760	R
Woodland	7	5YR 5/3		5YR 7/3	pink	20	25	.800	R
#2	8	5YR 5/3		5YR 6/3	light reddish brown	41	30	1.367	R
	9	5YR 5/3		5YR 7/3	pink	35	45	.778	R
Woodland	10	5YR 5/3		5YR 7/3		35	21	1.667	R
#3	11	5YR 5/3		5YR 6/3	light reddish brown	45	24	1.875	R
	12	5YR 5/3		5YR 7/3	pink	23	19	1.211	R
Thumb	13	5YR 5/3		5YR 7/3		15	27	.556	R
Lake	14	5YR 5/3		5YR 7/3		21	36	.583	R
	15	5YR 5/3		5YR 7/3		27	41	.659	R
Crego	16	5YR 5/3		5YR 7/3		22	22	1.000	R
	17	5YR 5/3		5YR 7/3		23	27	.852	R
	18	5YR 5/3		5YR 7/3		27	22	1.227	R
Zimmerman	19	10YR 5/3	brown	10YR 7/2	light gray	32	42	.762	B
	20	10YR 5/3		10YR 7/3	very pale brown	41	64	.641	B
	21	10YR 5/3		10YR 7/3		17	25	.680	B
Fleming	22	10YR 4/3	brown/ dark brown	10YR 6/3	pale brown	56	104	.538	B
	23	10YR 4/3		10YR 6/3		37	77	.480	B
	24	10YR 4/3		10YR 6/3		66	121	.545	B
Creighton	25	10YR 5/3	brown	10YR 7/2	light gray	30	56	.536	B
	26	10YR 5/3		10YR 6/3	pale brown	28	64	.438	B
	27	10YR 5/3		10YR 7/3	very pale brown	30	50	.600	B
Torch Lake	28	10YR 5/3		10YR 6/3	pale brown	45	55	.818	B
	29	10YR 5/3		10YR 6/3		45	79	.570	B
	30	10YR 5/3		10YR 6/3		53	62	.855	B
Plum Valley	31	10YR 6/4	yellow-ish brown	10YR 7/3	very pale brown	30	64	.469	B
	32	10YR 6/4		10YR 7/3		46	85	.541	B
	33	10YR 6/4		10YR 7/3		30	56	.536	B

*Peak counts minus background as determined by computer.

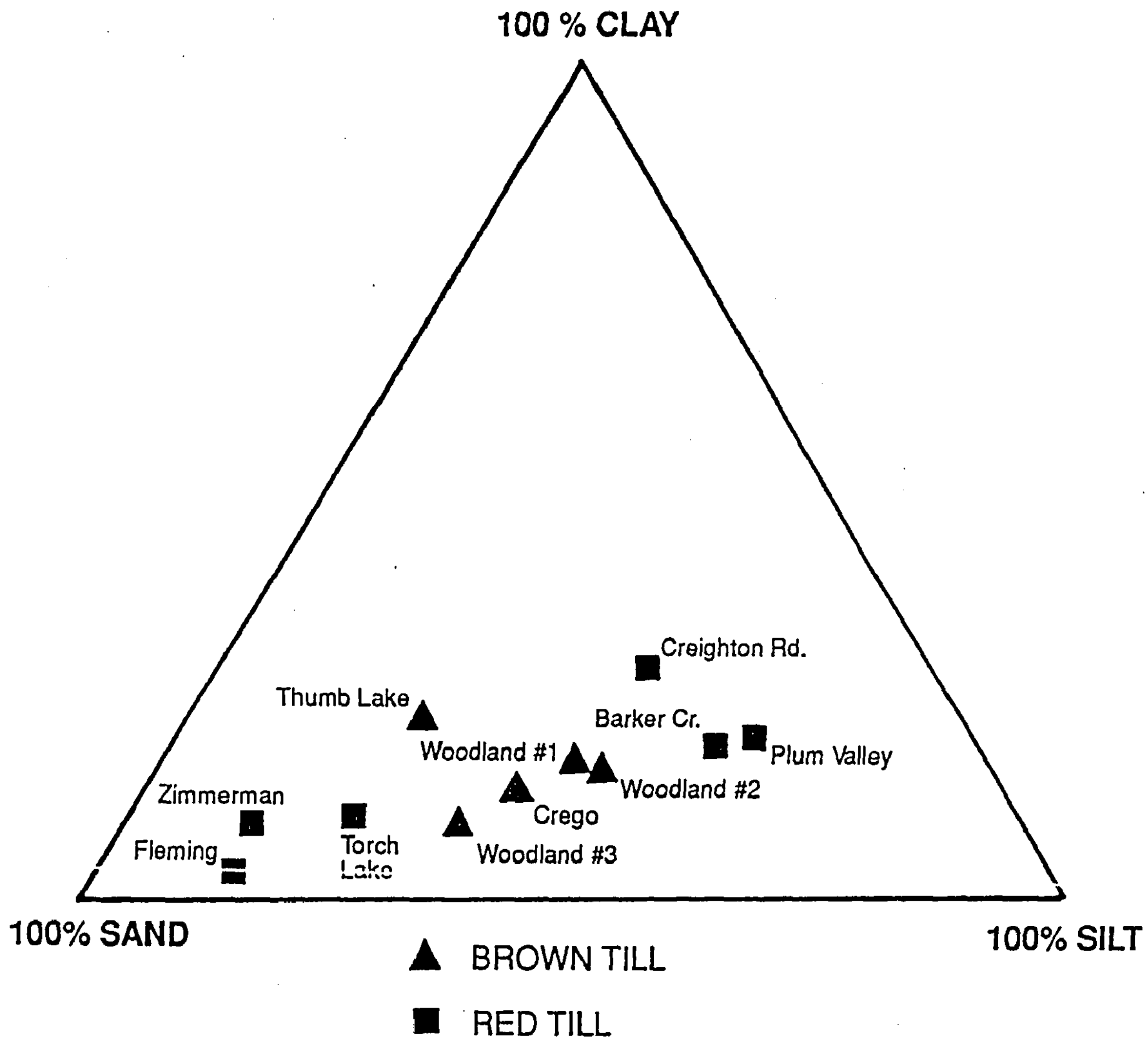

Figure 30. Soil textures of principal tills in the study area.

exposures are farther apart (10 km) and differ in altitude (273 m vs. 207 m, respectively). Data from Table 5 suggest that these samples may represent components of the same deposit, however. The remaining Creighton Rd. and Fleming Farm tills are both more than 24 km from other samples in their group. Correlation across such a distance is speculative.

Clay mineralogy - Thirty-three till samples from 11 sites were analyzed to determine composition of clay minerals. Preparation followed Glass (no date; see Appendix B) and results were interpreted using 7/10 Angstrom ratios (Rieck, 1976; Table 5).

One goal of the analysis was to investigate clay mineral differences between red and brown tills. Past researchers (Bretz, 1951; Berquist, 1953; Melhorn, 1954) interpreted brown and red tills as Port Huron and Valders (Greatlakean) deposits, respectively. Burgis (1977) recognized brown Port Bruce tills and red Port Huron and Greatlakean tills. Taylor (1981) noted a higher illite content in Port Huron (Orchard Beach) till than Greatlakean (Filer) till. Monaghan (1988) compared Greatlakean and Port Huron till along Lake Michigan and reported no differences in clay mineral composition.

Most red till from the study area exhibits 7/10 Å ratios ≥ 1.00, indicating high kaolinite and chlorite content (Fig. 31). Brown till ratios are always < 1.00 suggesting higher illite amounts, but moderate

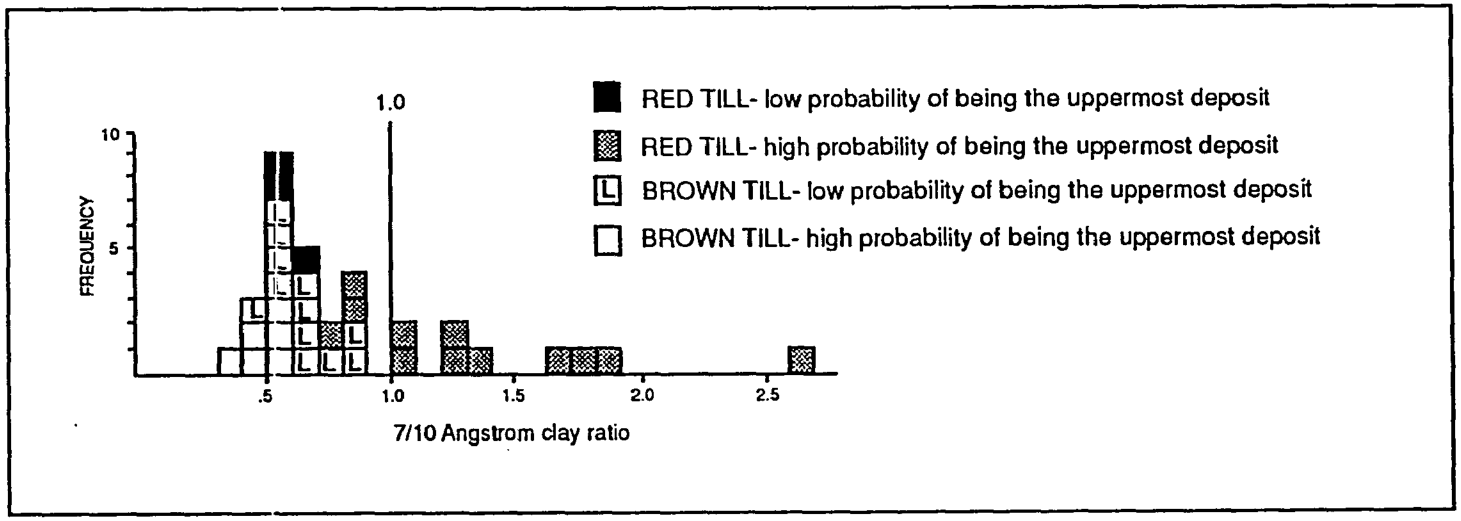

Figure 31. Frequency diagram of 7/10 Angstrom ratios for tills in the study area.

overlap (.5 to 1.0) precludes clear differentiation between the two tills. To complicate matters, brown tills come from widely scattered locations at varying altitudes, and may be of different ages; the latter also may be true for red tills. Thus, despite preliminary indications that red and brown deposits may be separated based on 7/10 Angstrom ratios, accurate understanding of till stratigraphy and mineralogy awaits more definitive study.

Summary

The Inner and Outer Port Huron Complexes are composed of thick drift overlying a moderate relief, northwest-southeast lineated bedrock surface. Present topography mimics bedrock form north of Mancelona, possibly due to higher bedrock relief and thinner drift here than in areas farther south. Individual thickness values are highest toward the north; average values become greater toward the south. Uppermost sand and gravel units form wedge-shaped deposits nearly 85 m thick along the Inner and Outer Port Huron crests. Where exposed, these units are unquestionably glaciofluvial in origin and are not sandy till. One possible pre-Late Wisconsinan till is identified at Rugg Pond.

Surficial sediments within areas mapped as moraine (Leverett and Taylor, 1915; Farrand and Bell, 1982) consist of ice-contact stratified drift and proglacial sand and gravel; till is very limited in extent and is usually in the form of flow till. Surficial sediments 1) are resting on a moderate relief clay surface that slopes towards the northwest, and 2) exhibit a distinct facies change apparent from both texture and bedform analysis. Thick lacustrine clays were deposited within a one kilometer wide zone proximal to the Inner and Outer Port Huron ice-contact slopes during deglaciation; those proximal to the Inner Port Huron feature are dated at 12,960 ± 350 yrs. B.P. All of these data indicate that the Inner and Outer Port Huron features are not classic end moraines but instead are complicated assemblages of landforms that evolved in association with abundant meltwater and stagnant ice during final deglaciation.

Chapter 3

LANDFORMS ASSOCIATED WITH THE INNER AND OUTER PORT HURON COMPLEXES

Principal landform units recognized in this study are the 1) Inner Port Huron Complex, including the Mancelona Plain, 2) Post Inner Port Huron zone, 3) Outer Port Huron Complex, and 4) fluted uplands and associated through valleys (Figs. 4, 32). Fluted uplands and associated through valleys are not discussed in detail because 1) they are ancillary to the study, and 2) little detailed field work was carried out in these areas.

Bedrock/landform relationships

As described in Chapter 2, the undulating, high relief (150 - 245 m) bedrock surface exhibits four subcropping linear lowlands, named the Kalkaska, Darragh, Alba, and Charlevoix valleys that trend either east-west or northwest-southeast (Fig. 6). West of the study area are broad bedrock lowlands associated with Grand Traverse Bay and Torch and Elk lakes.

Figure 33 shows that both the Inner and Outer Port Huron Complexes display a distinct salient and reentrant pattern. As defined here, salients delimit former projections of the ice margin and reentrants mark indentations. These features are named informally to aid discussion.

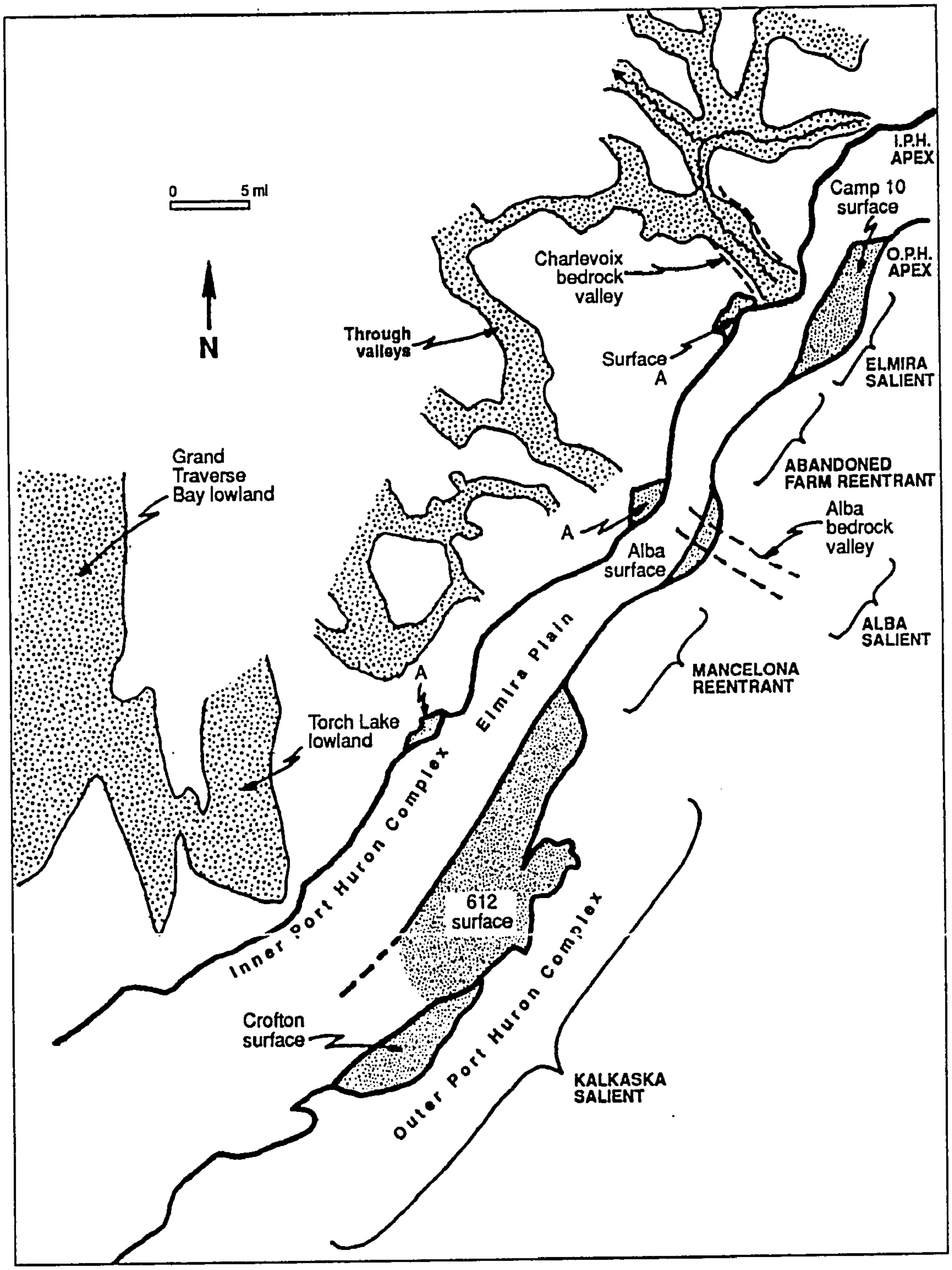

Figure 33. Relationship among salients, reentrants, through valleys, residual terraces, and bedrock valleys.

The extensive Kalkaska salient exhibits a broad arc, concave to the northwest that parallels the eastern flank of the bedrock lowland occupied by Grand Traverse Bay and Elk and Torch Lakes (Fig. 33). Farther north, the much smaller Elmira and Alba salients align, respectively, with the comparably sized northwest-southeast trending Charlevoix and Alba bedrock valleys.

Bedrock influence on ice marginal positions elsewhere has been documented by Kaye (1960), Koteff (1974), Rieck (1976), Cadwell (1978), Koteff and Pessl (1981), and Mulholland (1982). Coincidence between salients and bedrock valleys in the study area probably is due to thicker ice over valleys during advance, resulting in higher velocity and greater outflow. On these bases, some major landform trends in the study area are interpreted to be in large part the result of strong bedrock influence. For example, salients align with bedrock lowlands, reentrants with bedrock highs.

Landforms associated with the Inner Port Huron Complex

To facilitate discussion, the Inner Port Huron Complex is divided into 1) a proximal hummocky zone, and 2) distal terraced outwash plains (Mancelona Plain). Previously, these hummocky proximal zones were mapped as moraine (Leverett and Taylor, 1915; Martin, 1955; Farrand and Bell, 1982). Both areas are described and interpreted below.

PROXIMAL TRACTS

The crest of the Inner Port Huron Complex trends northeast-southwest for about 60 km. Altitudes range from 315 m in the southwest to 450 m at the apex of the interlobate tract. In cross-section the feature has a distinct asymmetrical profile, with a steep northwest-facing proximal slope and a gentle distal declivity (Fig. 13). Relief on the former exceeds 130 m at Deadman's Hill, where the Jordan River is at the base of the bluff. Numerous ice block depressions are associated with the slope, and at many locations boulders are concentrated along the crest.

In many places, the gentle distal slope displays hummocky topography nearest the crest. At the interlobate apex this zone is 4 km wide and contains numerous closed depressions and perforation features. Profiles show that the highest surfaces mark the remnants of an outwash plain that correlates with the Elmira Plain.

Southward, the hummocky zone narrows to a width of one kilometer near the Otsego-Charlevoix County line. Northwest of Mancelona, it widens again and contains ice-block depressions up to 20-30 m deep. Width of this area corresponds to the full breadth of the Mancelona Plain -- thus, where the plain is wide, so is the hummocky zone. Alternating areas of collapse and non-collapse topography (Fig. 32) are found farther south. High relief (38-44 m), uncontolled disintegration features are especially well developed near Mayville Lake (SW1/4, SW1/4, sec 26, T. 29 N., R. 7 W.).

Dry hanging valleys (Fig. 2), some nearly 15 m deep and 1 km long, are concentrated in three areas: 1) at the Inner Port Huron apex, 2) between Alba and Elmira, and 3) northwest of Mancelona (Fig. 32). None are identified south of Mancelona. Some hang nearly 75 m above the base of the declivity, many of the channels contain kettles, and all extend perpendicular to the trend of the ice-contact slope. Their impressive size, lack of a modern stream, and absence of a headwater area indicate formation by meltwater streams flowing off the ice margin. Furthermore, they are deepest and best developed at the steep proximal slope, indicating that the upstream portion of the valley must have been superglacial or englacial. No feeding eskers, crevasse fillings or other evidence for subglacial drainage are associated with the proximal slope where the hanging valleys are found.

In places, small alluvial fans, covering about a quarter survey section, extend southeast from the Inner Port Huron crest, adding an additional 10-15 m relief to the feature. These landforms have asymmetric fan-like profiles and are best displayed at Deadman's Hill (SW1/4, sec. 28, T. 31 N., R. 5 W.), near the junction of M-32 and US-131 (SE1/4, NE1/4, sec. 15, T. 31 N., R. 5 W.) and in the SE1/4, SW1/4, sec. 5, T. 28 N.,

R. 7 W. (Fig. 32). Similar landforms from other studies in Michigan are interpreted as sites where especially large superglacial streams deposited sand and gravel above the general sandur level during final deglaciation (Rieck, 1976; Blewett and Rieck, 1987). This explanation is appropriate for small alluvial fans in the study area.

Numerous linear ridges are identified proximal to the steep Inner Port Huron slope north and west of Mancelona. They are .5 - 1 km in length, oriented perpendicular to the Inner Port Huron bluff, and composed of ice-contact stratifed drift. Their morphology, composition, and close association with the Inner Port Huron proximal slope indicate formation as disintegration ridges in stagnant ice. Similar landforms have been described by, among others, Flint (1928), Price (1973), and Rieck (1976).

CONCLUSIONS

On the basis of 1) asymmetric alluvial fan-like profiles, 2) boulders along the Inner Port Huron crest, 3) evidence for ice-contact stratifed drift from Chapter 2, and 4) presence of stagnation landforms including dry hanging valleys, perched fans, ice block depressions, and feeding disintegration ridges, the steep proximal slope of the Inner Port Huron Complex is interpreted as an ice-contact slope. Associated hummocky topography eventually formed along the crest of the Inner Port Huron Complex from melting of ice blocks covered by drift during deglaciation. This indicates that proximal regions here are not morainic as mapped by others (Leverett and Taylor, 1915; Martin, 1955; Farrand and Bell, 1982), but instead mark terrain formed along a head of outwash as described by Koteff and Pessl (1981), and Blewett and Rieck (1987).

FLUVIAL AND GLACIOFLUVIAL SURFACES OF THE MANCELONA PLAIN

Leverett and Taylor (1915) applied the term "Mancelona Plain" to the valley train separating their Inner and Outer Port Huron moraines. Because the present study recognizes not one, but at least 10 distinct surfaces here, the term "Mancelona Plain" is used only when referring to the whole of this area. Since these surfaces have not been documented previously, they are described in detail below.

Three extensive, higher surfaces, and seven smaller, lower terraces are recognized based on detailed analysis of 7 1/2' topographic maps (3 and 5 m contours), field observation, and topographic profiles drawn at right angles to assumed flow direction (Fig. 34). The main surface, covering 75% of the Mancelona Plain, is informally named the Elmira Plain (Fig. 32). Except for the Crofton terrace and Hoffman Lake Channels, which are treated separately, all surfaces (including the Elmira Plain) are numbered sequentially from highest (#1) to lowest (#8).

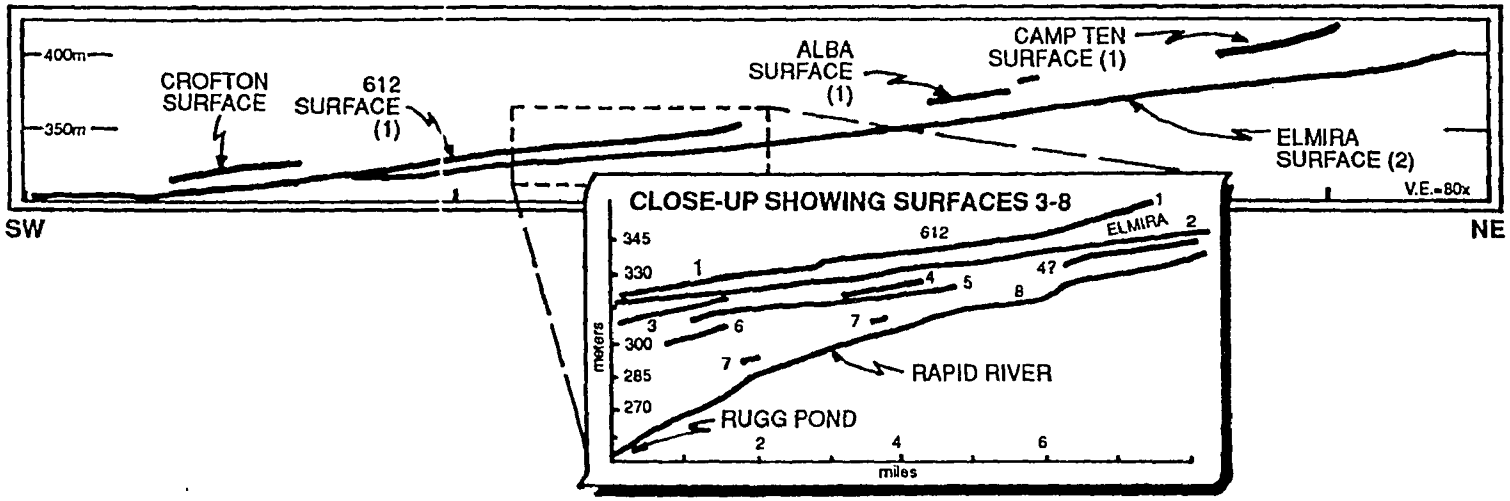

Figure 34. Principal surfaces of the Mancelona Plain.

<u>Crofton surface</u> -- The Crofton outwash surface, located immediately proximal to the Outer Port Huron Complex in Kalkaska County, is the uppermost terrace recognized on the Mancelona Plain. It slopes southwestward at 1.2 m/km and exhibits flat topography, broken by occassional shallow kettles and low sand dunes. Its steep proximal scarp contains no boulder concentrations or ice block depressions, suggesting it has been trimmed by subsequent meltwater erosion. Altitude and position of the Crofton feature relative to surface 1 (see next section), implies that this area was the first part of the Mancelona Plain to be deglaciated (see Ch. 4).

<u>Surface 1</u> -- Surface 1 is represented by three separate terraces (Camp Ten, Alba, and 612 surfaces), and correlated on the basis of profile alignment (Fig. 34). Overall slope, adjusted for 20% isostatic rebound since deglaciation (Leverett and Taylor, 1915), is approximately 1.5 m/km, and the surface merges with the Elmira Plain (surface 2) near Kalkaska (Fig. 34). Each of the three remnants is located immediately proximal to a major salient; large salients hold extensive terraces, small ones harbor smaller surfaces (Fig. 33). All are described briefly below. To simplify discussion, sediment data associated with each terrace are provided here instead of in Chapter 2.

CAMP TEN SURFACE: Located proximal to the Elmira salient (Fig. 33), this gently rolling tract lies 25 - 30 m above the Elmira Plain, and displays a steep proximal scarp devoid of ice block depressions or boulder concentrations. Melting of buried ice blocks and postglacial dissection have increased relief. Faint scroll marks, indicative of braided meltwater streams, are identified on aerial photographs and verify a glaciofluvial origin for the deposits.

Like the Elmira Plain, numerous stone piles, with some clasts exceeding 14 cm in b-diameter, are located at the edge of potato fields. Average b-diameter of 200 stones from four sampled piles (50 stones from each pile) was 7.8 cm. No significant pattern in average b-diameter is observable among stone piles across the surface, but sediments overall are much coarser than Alba and 612 deposits.

ALBA SURFACE: The Alba terrace is more dissected than the Camp Ten surface and lies 12 - 15 m above the Elmira Plain. Its steep proximal scarp lacks boulder concentrations or ice block depressions. A small gravel pit at the base of the proximal slope (NE 1/4, NE 1/4, sec. 29, T. 30 N., R. 5 W.) contains brown lacustrine clay, but surficial terrace deposits consist of sand and fine gravel, with a few clasts approaching 5 cm in b-diameter.

A second, higher surface, lying 18-21 m above the Elmira Plain, barely covers a quarter survey section, and is located on the northwest flank of the main Alba surface (Fig. 32). Because of its small size and uncertain significance, it is not included in discussions of surface 1 that follow.

612 SURFACE: This extensive, moderately kettled plain, exhibits a straight proximal scarp which is aligned with the northwest-facing slope of the Mancelona reentrant (Fig. 33). Southward, this terrace gradually merges with the Elmira Plain (surface 2, Fig. 34). Holocene dissection by headwaters of the Rapid River has increased the relief. Sediments are primarily sand with limited amounts of fine gravel.

Morphology and sediments indicate that these three terraces are remnants of a single outwash surface that was once more extensive. Evidence includes:

1. Terrace elevations become progressively lower southward (Fig. 34), producing a smooth concave-upward profile typical of outwash surfaces.

2. Terraces lack ice block depressions along proximal scarps, suggesting that these slopes are erosional, rather than ice-contact slopes.

3. Terrace scarps are aligned with truncated reentrants of the Outer Port Huron Complex (Fig. 33), indicating that scarps formed by meltwater trimming, rather than ice-contact deposition.

4. Terraces lack proximal boulder concentrations, indicating that proximal areas may not represent ice marginal positions.

5. Some terrace scarps exhibit a boulder lag proximal to the base of the slopes (Fig. 15), possibly indicative of meltwater trimming (see Ch. 4).

6. Sediments become progressively finer southward, based on visual reconnaissance, suggesting that these surfaces may mark remnants of an integrated glaciofluvial system.

7. Positioning of terraces within protected salients suggests that these surfaces were once more extensive. Even a slight expansion of these surfaces toward the northwest would unite the remnants in a single surface.

On all these bases, the Camp Ten, Alba, and 612 terraces are interpreted as remnants of a single outwash surface that was once more extensive (surface 1). Though superficially resembling kame terraces, the three surfaces exhibit morphology typical of outwash surfaces, and probably represent vestiges of an integrated glaciofluvial system that drained southwestward.

Elmira surface -- The Elmira surface is 75 km long, widens from 2 to 11 km toward the south, and slopes southwestward at 1.2 m/km. This slope is adjusted for isostatic rebound of approximately 20% based on 1) estimates of isostatic rebound from Leverett and Taylor (1915), and 2) an analysis of differential uplift of abandoned shorelines (located immediatley west of the study area) across latitudes corresponding to northern and southern boundaries of the study area. Northern and southern segments exhibit adjusted slopes of 1.5 m/km and 1.0 m/km, respectively (Fig. 34), producing the subtle concave-upward longitudinal profile typical of sandar (Fig. 35; Church, 1972). This low relief plain (Fig. 36) is puncutuated by scattered ice block depressions (with concentrations), erosional dry channels

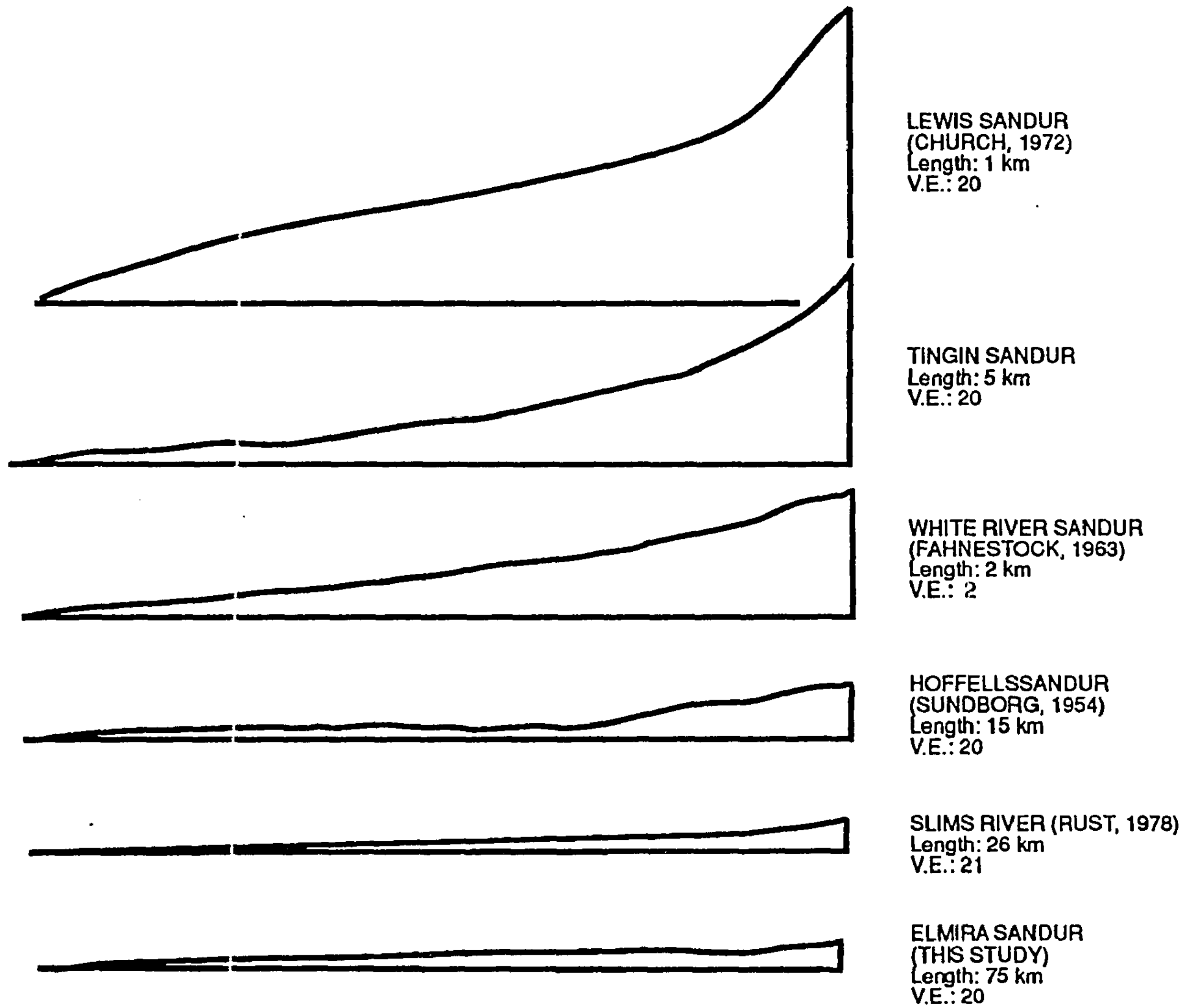

Figure 35. Profiles of selected sandar.

Figure 36. View southeastward across the Elmira Plain near Alba; the proximal slope of the Outer Port Huron Complex is in the distance.

in proximal areas north of Mancelona, and, southward, scattered dunes.

PRINCIPAL LANDFORMS OF THE ELMIRA SURFACE:

Kettle chains - Three kettle chains trend northwest-southeast across the Elmira surface northwest of Elmira (Fig. 32). These chains are more than 3 km long, with some depressions exceeding 30 m in depth, and display decreasing kettle bottom altitudes northwestward. The easternmost chain aligns with the trend of the through valley containing the Boyne River's South Branch.

Near Wetzel, a northwest-southeast oriented kettle chain containing Satterly Lake (SW1/4, sec 26, T. 30 N., R. 6 W.; Fig. 32), is aligned with Cascade Creek Gorge. Likewise, a nearby kettle chain containing Wetzel Lake aligns with the Green River Valley (Fig. 32).

Similar features elsewhere in Michigan are related to valleys in the pre-last advance surface (Rieck and Winters, 1979; Blewett and Rieck, 1987). In this interpretation, during deglaciation stagnant ice lingers longest in valleys and may be covered by outwash sediments. Gradual melting of this ice forms a series of linear kettles that mark the course of the pre-existing lowland. Alignment of kettle chains on the Elmira surface with through valley axes to the northwest is strong evidence for coincidence of bedrock lows and kettle chains. On these bases, kettle chains in northern sections of the Elmira Plain are interpreted as features likely marking the course of pre-existing lowlands.

Incised valleys - Numerous small incised valleys are identified on the Elmira Plain north of Mancelona. Most begin at the Inner Port Huron ice-contact slope as hanging valleys and trend southeastward (i.e. perpendicular to the former ice margin) across the Elmira Plain (Fig. 34). They average 5 m deep, 1 km long, and likely are graded to terraces lower than the Elmira surface (3-8). Maizels (1983b) interpreted similar features as non-equilibrium meltwater channels marking the transition to lower equilibrium surfaces. Likewise, the present study interprets incised valleys on the Elmira Plain as surfaces marking the transition from abandonment of the Elmira Plain to establishment of lower outwash terraces.

Terraces 3-8 -- Based on topographic data, six terraces lower than the Elmira surface are identified within a narrow zone centered on the headwaters of the Rapid River (Fig. 34). Surfaces 3, 4, 5, and 8 contain kettles and likely formed in association with stagnating ice. The first three surfaces comprise a stepped series of progressively lower terraces, each with curvilinear scarps concave to the northwest (Fig. 32). Downstream extensions of terraces 3, 4, and 5 are buried by stagnation topography west of Kalkaska. Evidence for burial includes 1) an abrupt downstream termination of relatively smooth outwash surfaces by uncontrolled disintegration topography, and 2) altitudes within these disintegration tracts that are much too high to correlate with surfaces 3, 4, and 5.

Burgis (1977) interpreted nearly identical landforms associated with the Au Sable River in northeastern Michigan as features marking the transition from wide, multiple-channel meltwater streams to single channel post-glacial streams controlled by precipitation and groundwater. Evidence for similar genesis of terraces 3-8 include 1) narrowing and increased sinuosity of successively lower surfaces, and 2) morphologic similarities between low altitude terraces (surfaces 7 and 8) and the modern Rapid River Valley. Significance of these landforms is discussed in Chapter 4.

Hoffman Lake Channel -- Eight hanging valleys along the Inner Port Huron apex converge southeastward to form the Hoffman Lake Channel (Fig. 32). This channel is .5 - 1.2 km wide, 8 km long, slopes south and eastward, and contains numerous shallow, dry kettles and kettle lakes. Two poorly developed terraces, higher than the main Hoffman Lake Channel, are identified at 365-370 m south of Heart Lake, and at 360-365 m north of Hoffman Lake. A small gravel pit in the highest surface contains imbricated gravels indicating drainage southward.

The 1) presence of dry hanging valleys at its upstream end, 2) large size, 3) presence of ice block depressions in the channel bottom, and 4) evidence for drainage south and east, indicates that the Hoffman Lake feature is a former meltwater channel, which drained an ice margin situated along the northwest flank of the Inner Port Huron apex.

Summary -- The extensive nature of surfaces 1 and 2 indicates that they are equilibrium surfaces, possibly related to quasi-stable ice marginal positions (Ritter, 1978; Maizel, 1983b). Kettle chains associated with surface 2 likely mark the trend of pre-existing lowlands. Hanging valleys and their distal extensions (small incised valleys) represent the transition from surface 2 to lower terraces. Terraces 3-8 most likely record the change from meltwater-dominated proglacial braided streams to precipitation/groundwater controlled non-glacial streams characterized by a single channel. The Hoffman Lake channel represents eastward drainage initiated sometime after abandonment of the Elmira surface. Interpretation and significance of these surfaces during final deglaciation is discussed in Chapter 4.

Landforms of the Post Inner Port Huron zone

Although this tract does not exhibit easily identifiable ice marginal heads of outwash, perched fans, hanging valleys, and proximal boulder concentrations like the Inner and Outer Port Huron Complexes, an approximate position for the ice margin can be inferred on the basis of outwash terraces incised into the Inner Port Huron ice-contact slope. The area's northwestern boundary is marked in most places by a sharp morphologic contrast between glaciofluvial terraces belonging to the Post Inner Port Huron zone and the separate fluted uplands.

Most outwash surfaces are associated with valleys of the Jordan, Green, and Cedar rivers and Warner Creek. All underfit, these streams occupy the bottoms of large, ancient ingrown meanders up to 1.6 km in amplitude (Fig. 37). Paleodischarges based on meander wavelength (Dury, 1965) in the Jordan Valley are approximately 17,800 to 33,600 $ft^3 sec^{-1}$, comparable to the modern Yellowstone River at Sidney, Montana.

Terraces here are correlated on the basis of profiles drawn at right angles to valley trend, and form a complicated array of small, isolated residual surfaces (Fig. 38). They can be divided into three types: 1) an extensive high-altitude terrace, A; 2) three medium-altitude transitional terraces, B, C, and D; and 3) twelve terraces associated with the Jordan-Warner and Cedar-Green river valleys: E, E1, F, FG, G, GH1, GH2, H, and W, X, Y, Z, respectively. With the general lack of verifiable ice marginal positions here and uncertainty as to the significance of Greatlakean/Valderan events, these terraces are described only briefly.

Figure 37. View from the Deadman's Hill overlook
of the underfit Jordan River with large paleomeanders.

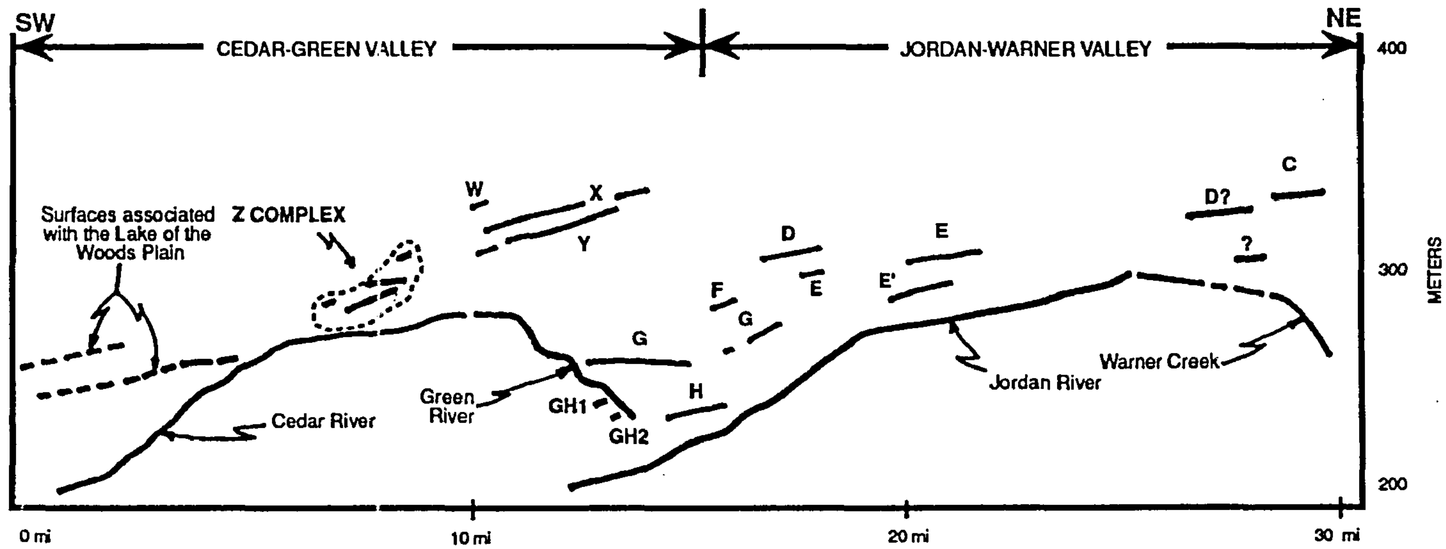

Figure 38. Principal glaciofluvial/fluvial surfaces of the Cedar-Green and Jordan-Warner valleys.

SURFACE A

This flat, southwest sloping surface (1.2 m/km adjusted slope) contains no proximal ice block depressions or crestal boulders like the Elmira Plain, and is best observed 1) on highway M-32, 0.5 km west of US-131, and 2) immediately north of Alba on Jordan River Road. At the latter location, the surface is associated with the Alba salient of the Inner Port Huron Complex, and shows that similar landform relationships exist between salients and outwash surfaces in both the Inner and Outer Port Huron Complexes. Southwestward, scattered terraces correlative with Surface A are identified along the base of the Inner Port Huron ice-contact slope.

SURFACES B, C, and D

Surface B is incised 20-25 m below surface A, and is best observed in the center of sec. 10, T. 31 N., R. 5 W. (Fig. 32). Surfaces C and D apparently mark the transition from higher, more extensive outwash surfaces (A and B) to lower, smaller fluvial terraces in the Cedar and Jordan River valleys (Fig. 38).

SURFACES OF THE CEDAR-GREEN RIVER VALLEY

Here, terraces W, X, and Y (Fig. 38) may correlate with a lower terrace assemblage (Z complex), but relationships are unclear. All are graded to an ice-contact lacustrine plain or kame delta (informally named Lake of the Woods Plain), with two distinct surfaces, one at 240-250 m, the other about 250-255 m (Figs. 32, 38).

The Lake of the Woods feature probably formed in a proglacial lake at the southern end of a through valley (the lowest part of which is now occupied by Lake Bellaire; Fig. 32). Associated ice-contact characteristics include 1) numerous kettles along its western margin, and 2) presence of a rim along the proximal scarp, suggesting mass wasting of sediments from marginally stagnant ice. In addition, no corresponding shorelines or lacustrine remnants are identified in the valley farther north, indicating that the proglacial lake was confined to the southern part of the valley and that tne remainder contained ice.

SURFACES OF THE JORDAN RIVER-WARNER CREEK VALLEY

Eight surfaces are recognized within the Jordan River Valley and are designated E, E1, F, FG, G, G-H1, G-H2, and H (Fig. 38). Surfaces E, E1, F, and G may be graded to a lacustrine plain, G. Like the Lake of the Woods Plain, surface G occupies the southern end of a major through valley, but ice-block depressions and other evidence of ice-contact formation are absent. The lake in which sediments accumulated to form surface G apparently was confined to the southernmost portion of the through valley, because neither corresponding shorelines nor lacustrine terraces can be identified in the valley farther north. Surfaces G-H1, G-H2, and H, along with the modern Jordan River, are incised into surface G.

SIGNIFICANCE OF POST INNER PORT HURON TERRACES

The complicated terrace assemblages within the Post-Inner Port Huron zone are difficult to interpret based on landform relationships alone. A complete explanation is not possible until there is a full and accurate understanding of Greatlakean/Valderan events in the area. In general, however, these terraces record the transition from a single, meltwater dominated braided system (surface A) to twin, non-glacial single channel streams of the Cedar-Green and Jordan-Warner valleys. Altogether, these surfaces 1) record the Pleistocene - Holocene transition in the study area, and 2) document, at least in part, final Port Huron deglaciation.

Landforms associated with the Outer Port Huron Complex

In cross section, the Outer Port Huron Complex has an asymmetrical topographic profile exhibiting a steep proximal scarp and gently inclined distal slope (Fig. 13). Most proximal terrain exhibits a 1-2 km wide hummocky zone, which grades distally into outwash plain. As described below, morphologic profiles and sedimentary data (Chapter 2) indicate that northern areas are characterized by a single prominent ice marginal position, whereas southern regions display landforms associated with a series of successive glacial terminii. On these bases, the Outer Port Huron Complex is divided into 1) a northern proximal region, 2) a northern distal region, and 3) southern tracts composed of numerous isolated heads of outwash. Each is described and interpreted below.

NORTHERN PROXIMAL REGIONS

To facilitate discussion, proximal areas are divided into seven subregions based on topography and salient/reentrant associations (Fig. 32).

Fleming Disintegration Ridges (Sec 10, T. 31 N., R. 4 W.; Fig. 32) - These ridges, averaging 1 km long, 150 m wide, and 10 m high, are confined to proximal areas of the Outer Port Huron apex. Oriented both northwest-southeast and north-south, some coalesce southward forming "Y" shaped landforms in map view (Fig. 32). Sediments are ice-contact stratified drift (Fleming Farm gravel pit; Ch. 2), and numerous boulders ≥ 0.5 m are on and between ridges. Gravenor and Kupsch (1959) attributed formation of similar features to deposition of superglacial sediment within crevasses in stagnant ice.

Lake 27 Disintegration Ridges (Sec 27, T. 31 N., R. 4 W.) - These large, controlled disintegration features form a polygonal ridge pattern containing intervening ice-block depressions covering nearly 6 km^2 (Fig. 32). Ridges are generally oriented northwest-southeast and east-west. Single ridges can be followed 3 km or more, may reach altitudes of 425 m, and display relief up to 42 m. Such features probably record crevasse patterns in stagnant ice as described by Kaye (1960).

Elmira South Apron (SW1/4, sec 36, T. 31 N., R. 5 W.) - Here, the topography consists of perched fans, hanging valleys and a steep (70 - 80 m relief) proximal bluff exhibiting crestal boulders. All are unmistakeable evidence for an ice-contact slope. Little buried ice was present here because proximal hummocky zones are absent and few kettles are identified. Thus, this landform assemblage represents a head of outwash, unassociated with significant amounts of buried ice, which formed along a stagnant glacial margin.

Abandoned Farm Hummocks (Sec. 10, T. 30 N., R. 5 W.) - Uncontrolled disintegration topography exists near an abandoned farm northeast of Alba (Figs. 32, 39). Kaye (1960, p. 372) attributed genesis of similar landforms to differential deposition of superglacial sand and gravel from an ice mass of uneven thickness. Scattered outcrops near here reveal such deposits.

Alba Salient (Secs 27, 28, T. 30 N., R. 5 W.) - This area is characterized by a complex of incised dry channels, shallow kettle chains, and subtle but large disintegration features. Numerous boulders are concentrated near the road separating sections 15 and 22, T. 30 N., R. 5 W. (Fig. 15), and, combined with morphology, provide strong evidence for a former ice marginal position here. Scattered exposures show stratifed sand and coarse gravel. On these bases, landform genesis is interpreted to be similar to the Abandoned Farm Hummocks, except that

Figure 39. View of proximal hummocky topography
at the Abandoned Farm site in the Outer Port Huron Complex.

the Alba salient experienced further alteration by stream dissection possibly initiated by a falling water table upon deglaciation (described in Chapter 4).

Alba South Apron (Secs. 4, 5, 7, 8, 17, and 18, T. 29 N., R. 5 W.) - Southward, the Outer Port Huron Complex exhibits a steep proximal ice-contact slope with crestal boulders and gently sloping distal plains. A northwest-southeast oriented hanging valley is located in the NW1/4, sec. 17, T. 29 N., R. 5 W. Landform assemblages here are similar to the Elmira South Apron and are interpreted in the same manner.

Mancelona Reentrant (Secs 14, 15, and 22, T. 29 N., R. 6 W.) - Here, the proximal slope of the Outer Port Huron Complex only approximates a former ice marginal position because it has been truncated by meltwater streams on the Mancelona Plain. Disintegration ridges in the proximal zone exhibit a weakly developed north-south orientation and relief approaches 15 m. Landform genesis is similar to the Abandoned Farm Hummocks.

Summary -- Altogether, these seven regions are distinguished on the basis of the 1) nature of the associated proximal slope (ice-contact vs. eroded), 2) influence of buried ice on topography, 3) presence of controlled vs. uncontrolled topography, 4) amount of post-glacial dissection, and 5) relation to salients and reentrants. Characteristics of each are presented in Table 6.

TABLE 6. CHARACTERISTICS OF PROXIMAL SUBDIVISIONS OF THE OUTER PORT HURON COMPLEX.

Area	Type of proximal slope	Influence of buried ice	Type of disintegration	Amount of post glacial dissection	Salient or reentrant location
Fleming Disint. Ridges	ice-contact	significant	controlled	not significant	reentrant
Lake 27 Disint. Ridges	erosional	significant	controlled	not significant	salient
Elmira South Apron	ice-contact	not significant	(not present)	not significant	southeast side of salient
Abandon Farm Hummocks	erosional	significant	weakly controlled to uncontrolled	not significant	reentrant
Alba Salient	mostly erosional	significant	weakly controlled to uncontrolled	significant	salient
Alba South Apron	ice-contact	not significant	(not present)	not significant	southeast side of salient.
Mancelona Reentrant	erosional	significant	uncontrolled to weakly controlled	significant along margin	reentrant

With minor exceptions, only the Elmira South and Alba South aprons exhibit a true ice-contact slope. Elsewhere along the Outer Port Huron proximal acclivity the 1) alignment of terrace scarps on the Mancelona Plain with the Outer Port Huron bluff, 2) presence of a boulder lag just west of the Outer Port Huron slope, 3) smooth, curvilinear form (concave to the west) to parts of this acclivity, and 4) lack of boulders along the Outer Port Huron crest, all indicate that the slope has been altered by subsequent meltwater erosion.

Interestingly, the similar Elmira South and Alba South landform assemblages are located in the same location relative to their respective salients; reasons for this are unclear. Reentrant regions display strongly lineated controlled disintegration topography east of Elmira and much weaker alignment southward. The Alba and Elmira salients generally contain larger disintegration ridges and greater post-glacial stream dissection than reentrants. These regions also tend to have the most rugged topography because they overlie bedrock valleys, which were preferred areas for burial of ice.

NORTHERN DISTAL REGIONS

In distal regions, the Outer Port Huron outwash plain has flat to gently rolling topography punctuated by numerous deep kettles, a few kettle chains, and many dry valleys. Unadjusted gradients for the southeast sloping outwash surface are approximately 3.1 m/km. The Manistee

River is at the distal edge of the plain and marks the southwestward route of former meltwater drainage. Isolated small hills in the area are interpreted to be partially buried outliers of the older Grayling uplands centered farther east (Fig. 32).

Lakes of the North margin (Secs 9, 10, T. 29 N., R. 5 W.) - A series of small, scattered alluvial fans of outwash (Fig. 32) with proximally feeding disintegration ridges attain altitudes of 420 m near Lakes of the North Resort, about 3 km distal to the Outer Port Huron ice-contact slope. Sediments are coarse textured, with boulders concentrated on disintegration ridges and along ice-contact slopes. Altogether, these landforms are interpreted as an ice marginal terminus formed prior to the main Outer Port Huron position.

MULTIPLE MARGINS OF THE SOUTHERN OUTER PORT HURON COMPLEX

From Manistee Lake southward, the Outer Port Huron Complex consists of an assemblage of mostly small, isolated heads of outwash that collectively mark five ice marginal positions (Fig. 32). Profiles drawn at right angles to overall landform trend (Fig. 40) show the diagnostic imbricate-like morphology typical of morphosequences (Koteff and Pessl, 1981). With the possible exception of position 1, all show significant erosion by subsequent meltwater streams. This is best observed in the northern half of sections 35 and 36, T.

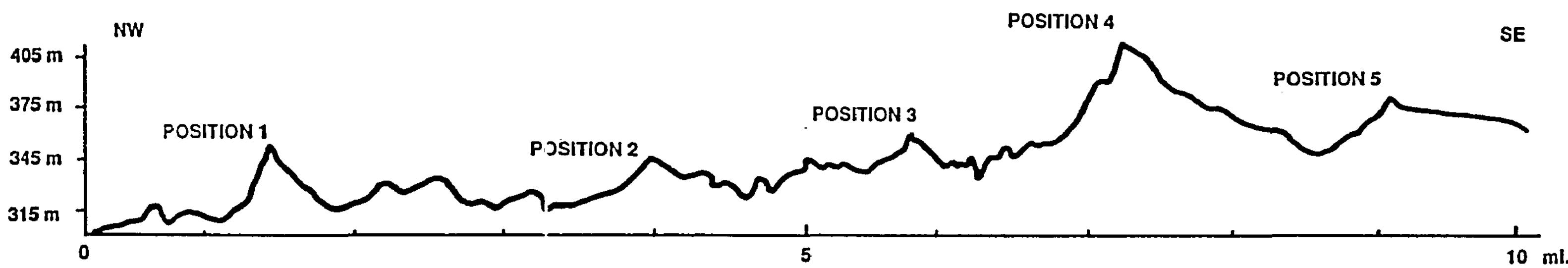

Figure 40. Profile across the Outer Port Huron Complex.

26 N., R. 8 W., where a southwest-trending dry channel is cut into the base of position 3. Characteristics of all five margins are shown in Table 7. Together, these five positions are interpreted as terrain formed along a series of successive marginally stagnant glacial terminii.

SUMMARY

The Outer Port Huron crest marks an especially important head of outwash that is graded to the Outer Port Huron outwash plain (Fig. 32). Thus, it is not a moraine flanked by distal outwash as mapped by others (Leverett and Taylor, 1915; Martin, 1955; Farrand and Bell, 1982). The steep, proximal acclivity is a true ice-contact slope, unmodified by subsequent meltwater erosion, in only a few places, however. Many proximal areas display hummocky topography formed by differential deposition of superglacial sand and gravel from an ice mass of uneven thickness. Overall, morphology and sediments indicate that ice marginal positions were more transitory toward the south, with terrain here forming along a series of five successive marginally stagnant glacial positions.

Conclusions

Regionally, salient and reentrant landform patterns are directly related to subsurface bedrock topography. Large salients are associated with extensive bedrock

TABLE 7. CHARACTERISTICS OF MULTIPLE ICE-MARGINAL POSITIONS.

Position	Location	Morphology	Sediments
1	Southern extension of main Outer Port Huron position	42-48 m relief, closed depressions, disintegration ridges, perforation features, hanging valleys, kettles	glaciofluvial sand and gravel, glaciolacustrine silt and clay, random boulder distributions
2	Sec. 10, T. 26 N., R. 7 W.	390 m in altitude, landforms same as position 1	glaciofluvial sand and gravel, crestal boulders
3	Sec. 36, T. 26 N., R. 8 W.	30 m relief, 354 m in altitude, landforms same as position 1	glaciofluvial sand and gravel, glaciolacustrine silt and clay, crestal boulders
4	Secs. 5 and 6, T. 25 N., R. 7 W.	69 m relief, 417 m in altitude, highly dissected, landforms same as position 1	same as 3 but no crestal boulders observed
5	SE 1/4, sec. 33, T. 26 N., R. 7 W.	36 m relief, 381 m in altitude, landforms same as position 1	same as 4

lowlands, smaller salients with less extensive bedrock valleys. These, in turn, are directly related to the size of terrace remnants (Camp Ten, Alba, and 612 surfaces) associated with each salient.

The presence of 1) steep, proximal ice-contact slopes, 2) hanging valleys, 3) perched fans, 4) imbricate, asymmetrical topographic profiles, and 5) widespread disintegration landforms indicate that topography of the Inner and Outer Port Huron Complexes formed along marginally stagnant ice characterized by abundant meltwater and superglacial drift during final deglaciation, in a fashion described by Price (1973), and Blewett and Rieck (1987).

Crests of both the Inner and Outer Port Huron features trend more than 50 km and mark important heads of outwash graded to the Elmira Plain and Outer Port Huron outwash plain, respectively. The notion that each feature is a moraine with distally flanking outwash is unsupported.

Despite such similarities, major differences exist between the two features. In most places, the Inner Port Huron proximal acclivity is interpreted as an ice-contact slope, whereas the Outer Port Huron bluff has been modified significantly by subsequent meltwater erosion. Proximal zones in the Outer Port Huron feature are wider and more variable than corresponding tracts along the Inner Port Huron margin, and only the former exhibits controlled disintegration. In addition, the broad outwash plains of the Outer Port Huron Complex contrast sharply with the narrow valley train associated with the Inner Port Huron position.

Leverett and Taylor's Mancelona Plain contains two principal equilibrium outwash surfaces (1 and 2), along with 8 recognized ancillary terraces. Surfaces 1 and 2 are extensive, regionally significant landforms covering hundreds of square kilometers. Their great size and the thickness of associated deposits indicate that they formed over a relatively long time period. In contrast, ancillary terraces cover limited areas and, based on regional landform patterns, most probably mark a relatively brief transition period from glacial to non-glacial conditions, characterized by rapid incision and falling water tables.

Chapter 4

PROPOSED DEGLACIATION AND LANDFORM DEVELOPMENT IN THE STUDY AREA

Final deglaciation events are divided into six successive phases:

1. Formation of the Outer Port Huron Complex;
2. Formation of surface 1;
3. Formation of the Inner Port Huron Complex;
4. Formation of the Post Inner Port Huron zone;
5. Formation of disintegration topography west of Kalkaska;
6. Postglacial modification of the landscape.

As discussed in Chapter 2, final deglaciation was characterized mainly by thick glaciofluvial deposition upon an uneven clay surface inclined toward the northwest (Fig. 13). The subcropping sediment is probably till that was deposited either during 1) Port Huron advance and/or retreat, or 2) an earlier Late Wisconsinan glaciation (Port Bruce?).

Two modes of deposition most likely account for the pattern of overlying glaciofluvial sediments:

1) Infilling along a quasi-stable, marginally stagnant glacial position (Fig. 41a), or

2) Deposition along a steadily retreating ice margin (Fig. 41b).

Evidence presented below indicates that aspects of both models may account for deglaciation in the study area.

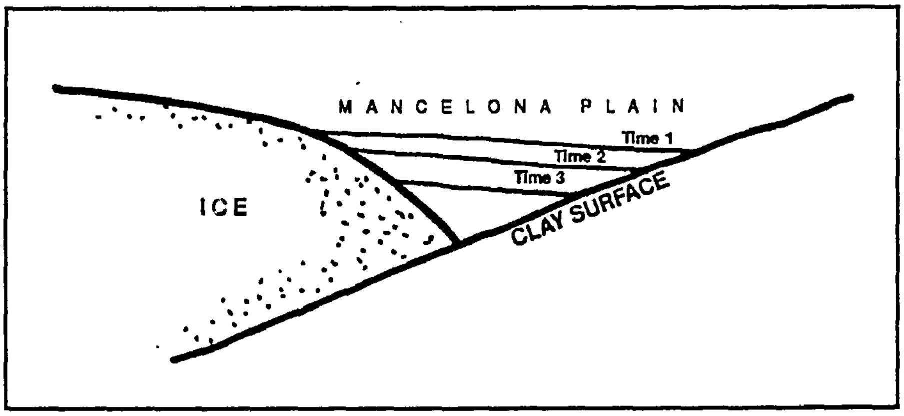

Figure 41A

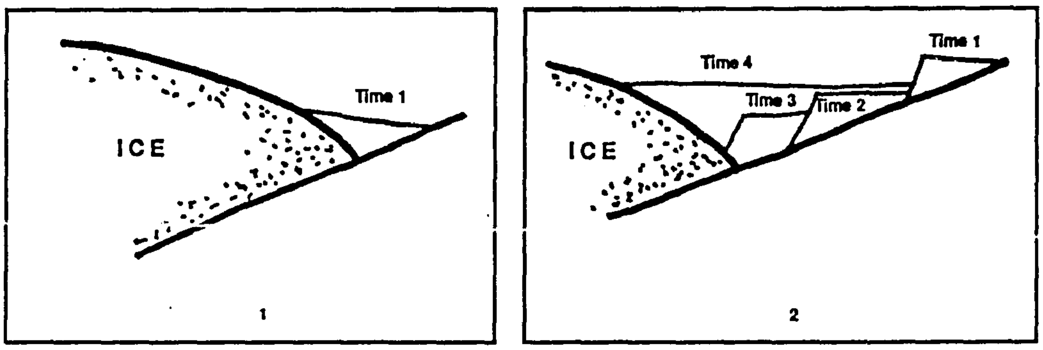

Figure 41B

Figure 41. Models of deposition for the Mancelona Plain

The precise maximum position of Port Huron ice cannot be determined on the basis of morphology and the limited sedimentological data available. For this reason, interpretations of deglaciation begin with formation of the oldest recognized ice marginal landforms in the Outer Port Huron Complex. Port Huron ice may, however, have advanced farther east, a view supported by similarities in regional trends of the Port Huron Complexes and the older Grayling uplands as mapped by Leverett and Taylor (1915), Martin (1955), and Farrand and Bell (1982). Events of final deglaciation, discussed below, are based on morphologic, stratigraphic, and chronologic evidence presented in preceeding chapters.

Phase 1

Positions 5 - 1, shown in Fig. 42, mark a series of successive ice marginal positions in southern sections of the Outer Port Huron Complex. Here, meltwater from younger margins has eroded older heads of outwash. Controlled disintegration ridges, many oriented perpendicular to the ice terminus, also formed within areas of stagnant ice. Eskers, which usually are indicative of subglacial drainage, are not identified. Their absence may be explained either by 1) burial of these landforms by superglacial drift, or 2) meltwater sources that were primarily superglacial.

In contrast, to the north the position of the ice margin remained relatively stable. That is, after

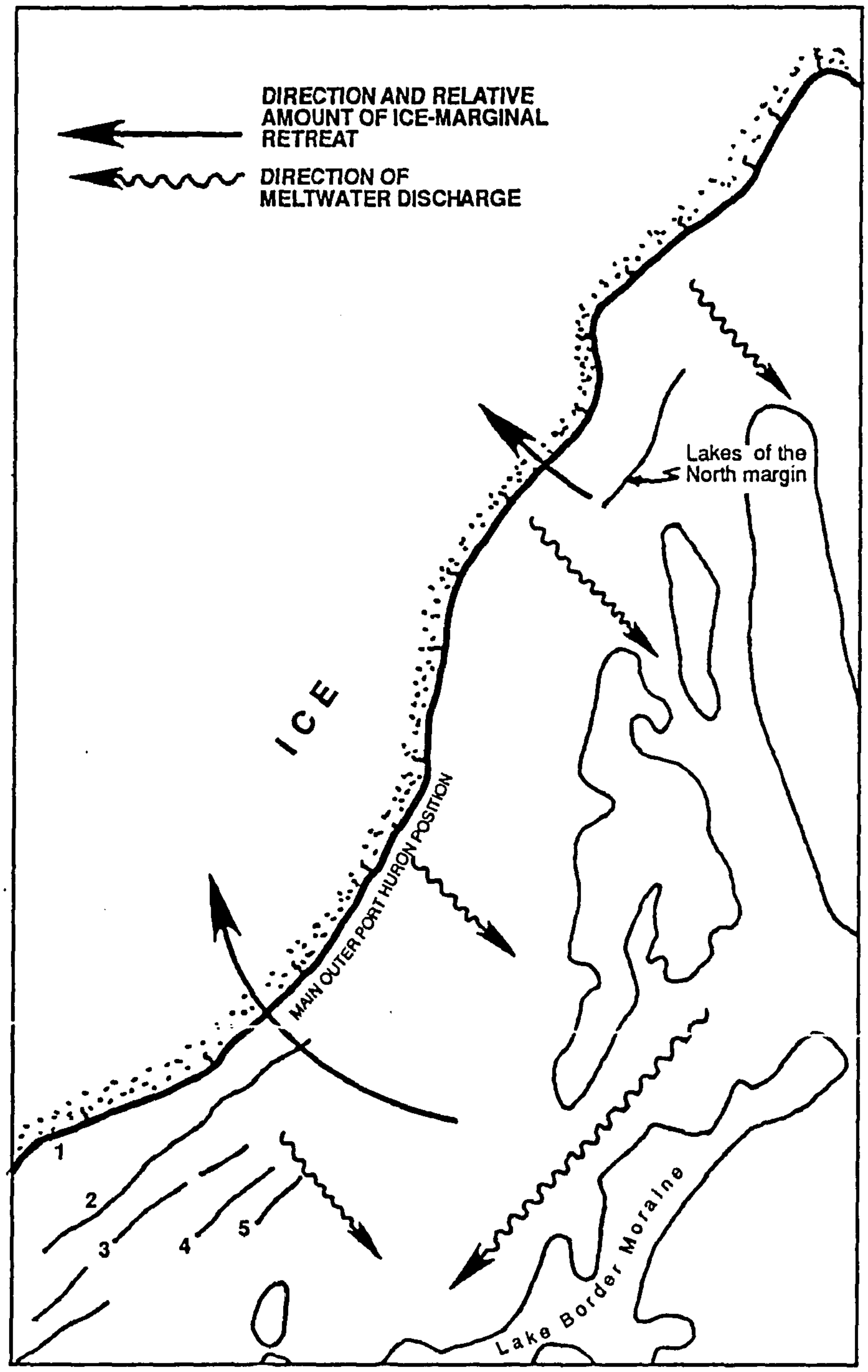

Figure 42. Phase 1. Formation of the Outer Port Huron Complex

forming the Lakes of the North outwash aprons, the glacial margin retreated to the main Outer Port Huron position early in phase 1, and did not produce a series of ice-marginal landforms similar to those farther south. As a result the topography here is both distinct and prominent and may have formed within several centuries.

With the exception of the Lakes of the North features, northern areas exhibit an extensive outwash plain with a steep proximal acclivity formed along a single, relatively stable, stagnant ice margin. The southern region, however, contains an assemblage of smaller, separate, less prominent heads of outwash marking five successive marginally stagnant glacial positions. This indicates that the ice margin probably rotated clockwise to the northwest during deglaciation (Fig. 42). Terrace patterns on the Mancelona Plain indicate that this style of marginal retreat was not confined to the Outer Port Huron Complex, but characterized deglaciation throughout southern regions of the study area.

Hummocky proximal tracts in the Outer Port Huron Complex display controlled and uncontrolled disintegration topography composed of ice-contact stratified drift. Church (1972) and Price (1973) attributed formation of similar landforms to outwash plains originating on the ice surface a short distance up-ice from the glacial margin. Likewise, glaciofluvial sediments of the Outer Port Huron outwash plain were probably deposited over a relatively thin layer of stagnant ice, which, upon melting, produced the proximal hummocky topography observed today.

The 1) alignment of eroded terrace scarps on the Mancelona Plain with truncated proximal slopes of Outer Port Huron reentrants (Figs. 32, 33), 2) absence of crestal boulders along large segments of the Outer Port Huron Complex, and 3) presence of a boulder lag along the base of the Outer Port Huron proximal slope indicate that in most places the Outer Port Huron bluff is not a true ice-contact slope. Although it marks the general position of the ice margin, this acclivity has been modified significantly by meltwater erosion.

Numerous hanging valleys are also associated with the crest of the Outer Port Huron feature, implying that meltwater erosion increased just prior to abandonment of the Outer Port Huron Complex. Because meltwater streams associated with stagnating ice usually become less vigorous over time, this incision likely reflects a decreasing sediment supply. These valleys must mark the very last meltwater streams, otherwise they would have been altered by later events.

Meltwater from the Outer Port Huron Complex was diverted southwest by the older Lake Border Moraine (Fig 42), following a course similar to the modern Manistee River. Burgis (1977) correlates the associated outwash surfaces with the Glenwood II Stage of Lake

Chicago in the Lake Michigan basin.

A complex progression of proglacial lakes formed between the ice and the Outer Port Huron slope in the south as the glacial terminus was rotating northwestward, their size, depth and altitude being controlled by positioning of the ice margin. Further ice-marginal retreat opened lower outlets, drained the lakes, and initiated meltwater drainage on the Crofton outwash surface (Fig. 43).

Phase 2

Eventual deglaciation of the main position farther north initiated fosse drainage proximal to the Outer Port Huron slope, forming surface 1 (Camp Ten, Alba, and 612 terraces, Fig. 44). The corresponding position of the ice margin associated with this surface (Fig. 44) is interpreted on the basis of the following evidence:

1) because the three terraces are remnants of surface 1, the latter must have been more extensive. Such dimensions require a prominent, regionally significant head of outwash somewhere proximal to the Outer Port Huron Complex.

2) It is unlikely that this ice margin was located at the Inner Port Huron position because surface 1 would have had to cover the entire Mancelona Plain. Subsequent formation of the lower Elmira surface would require the erosion of a sediment volume averaging 15 m thick, 75 km long and 6 km wide, an amount that seems excessive given estimates of paleodischarge (this study) and age constraints for Port Huron events from other studies elsewhere.

3) a boulder lag on the Elmira surface, just proximal to the Alba and Camp Ten scarps, probably marks the former ice marginal position. This explanation assumes that Elmira meltwater streams have eroded the ice-marginal portions of the two

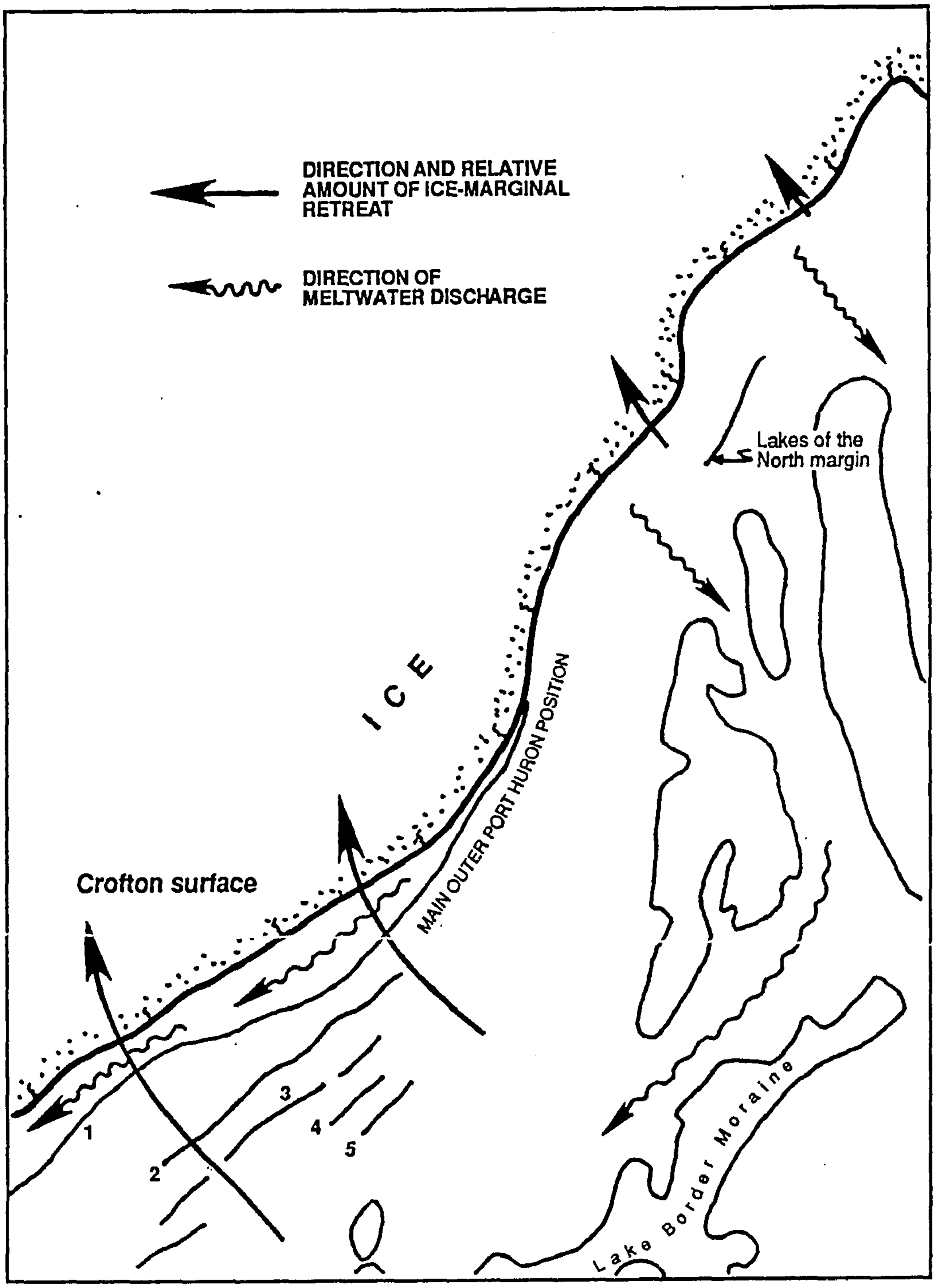

Figure 43. Formation of the Crofton surface

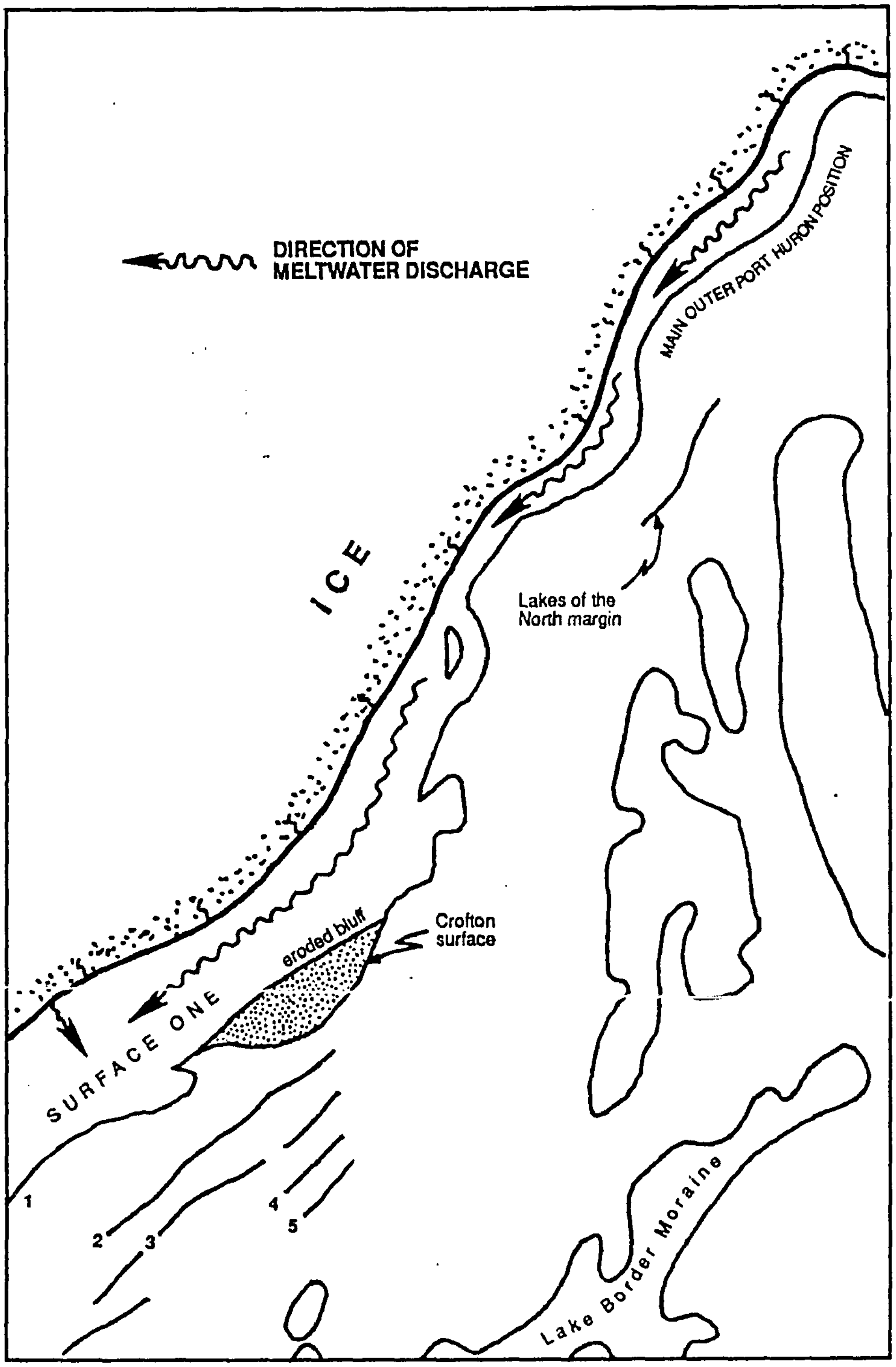

Figure 44. Phase 2. Formation of Surface 1.

> terraces. Boulders concentrated at the glacial margin were too large for stream transport and remained as residuals that delimit the former ice position.

This evidence suggests that the ice margin associated with Phase 2 be placed somewhere between the Outer and Inner Port Huron positions. If correct, a glacial margin here supports the idea that deposition occurred along a steadily retreating glacial terminus (Fig. 41b).

<u>Phase 3</u>

Ice marginal retreat to the Inner Port Huron position resulted in 1) the end of glaciofluvial deposition on surface 1, 2) an unknown amount of erosion on the terrace scarps, and 3) the formation of the Elmira Plain (Fig. 45). The extent, thickness, and volume of sediments associated with the Inner Port Huron Complex suggest that it formed during an equilibrium period of significant duration, possibly lasting several centuries. If so, deposition of Elmira sediments may have followed the successive infilling model shown in Figure 41a. The location and distribution of 1) ice-contact stratified drift, 2) crestal boulder concentrations, 3) dry hanging valleys, 4) perched fans, 5) feeding disintegration ridges and 6) evidence for minimal subsequent meltwater erosion, indicate that the Inner Port Huron proximal declivity is in most places an ice-contact slope.

Farrand and Eschman (1974) trace the Elmira surface (which they call the Mancelona Plain) southwest to Manistee, and Burgis (1977) correlates it with the

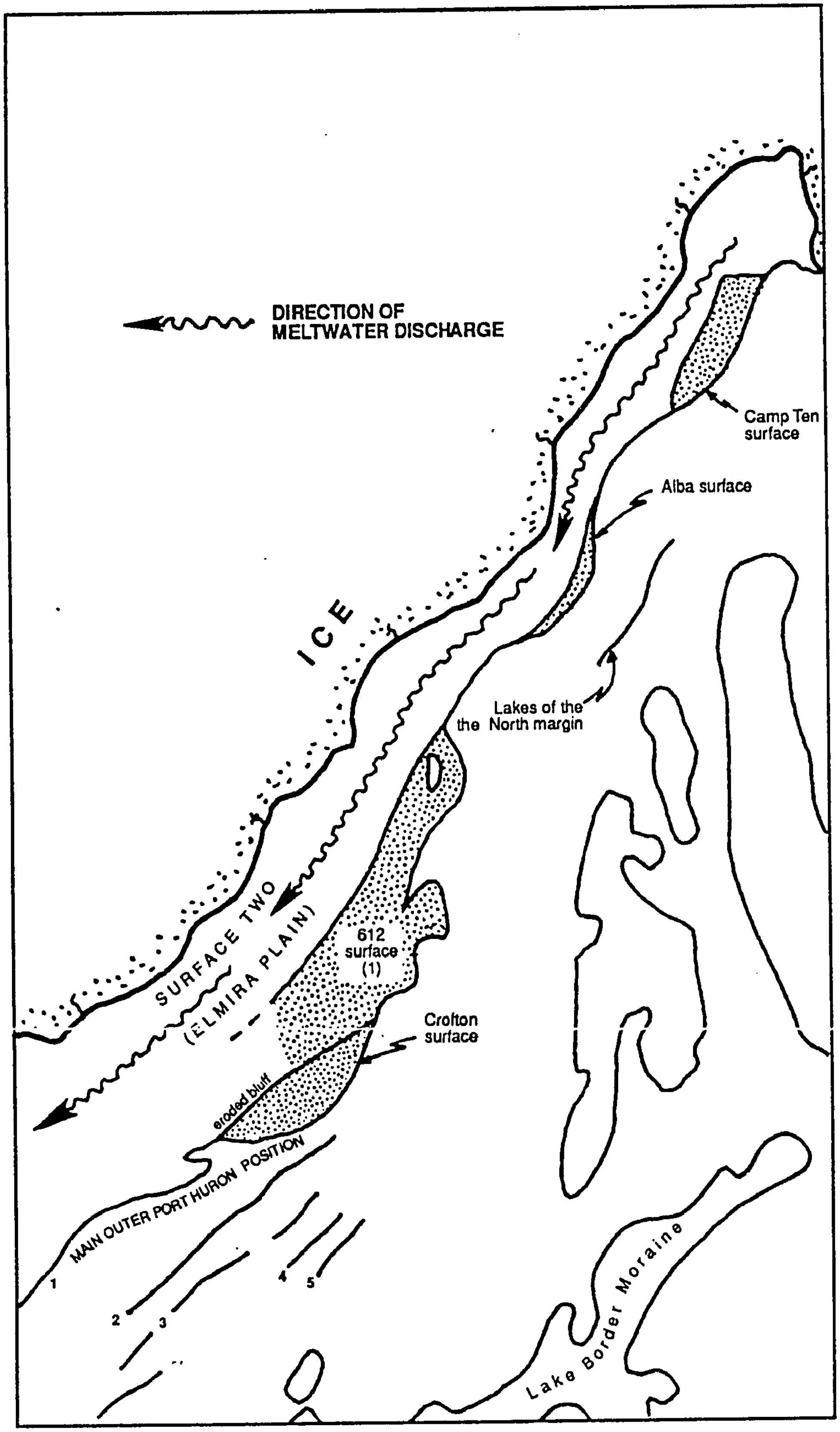

Figure 45. Phase 3. Formation of Surface 2.

Glenwood II stage of Lake Chicago. With deglaciation of the Inner Port Huron Complex, lower meltwater outlets were opened, and the Elmira Plain was abandoned (Fig. 46). Surfaces 3, 4, and 5 mark the transition to these lower outlets.

The 1) pattern of surfaces 3, 4 and 5 (Fig. 32) and 2) relationship of these surfaces with the small incised valleys described in Chapter 4 indicate that ice-marginal retreat from the Inner Port Huron Complex progressed from south to north, thus continuing the previously established northwestward pivoting motion (Fig. 46). Near Mancelona (secs. 5 and 6, T. 29 N., R. 6 W.), headward portions of some incised dry channels carved by superglacial meltwater are nearly 70 m above the base of the ice-contact slope. These channels extend southeastward onto the Elmira Plain and are incised into its surface. Their downstream ends eventually merge with the complicated terrace assemblage marking surfaces 3, 4, and 5. If these latter surfaces are followed southwestward, their downstream portions lie proximal to the Inner Port Huron ice-contact slope. Thus, meltwater streams draining the ice margin at the Inner Port Huron position west of Mancelona lie proximal to this margin farther south. In combination the arrangement of these landforms suggests that ice remained at the Inner Port Huron position west of Mancelona, while a similar position already had been abandoned farther south (Fig.

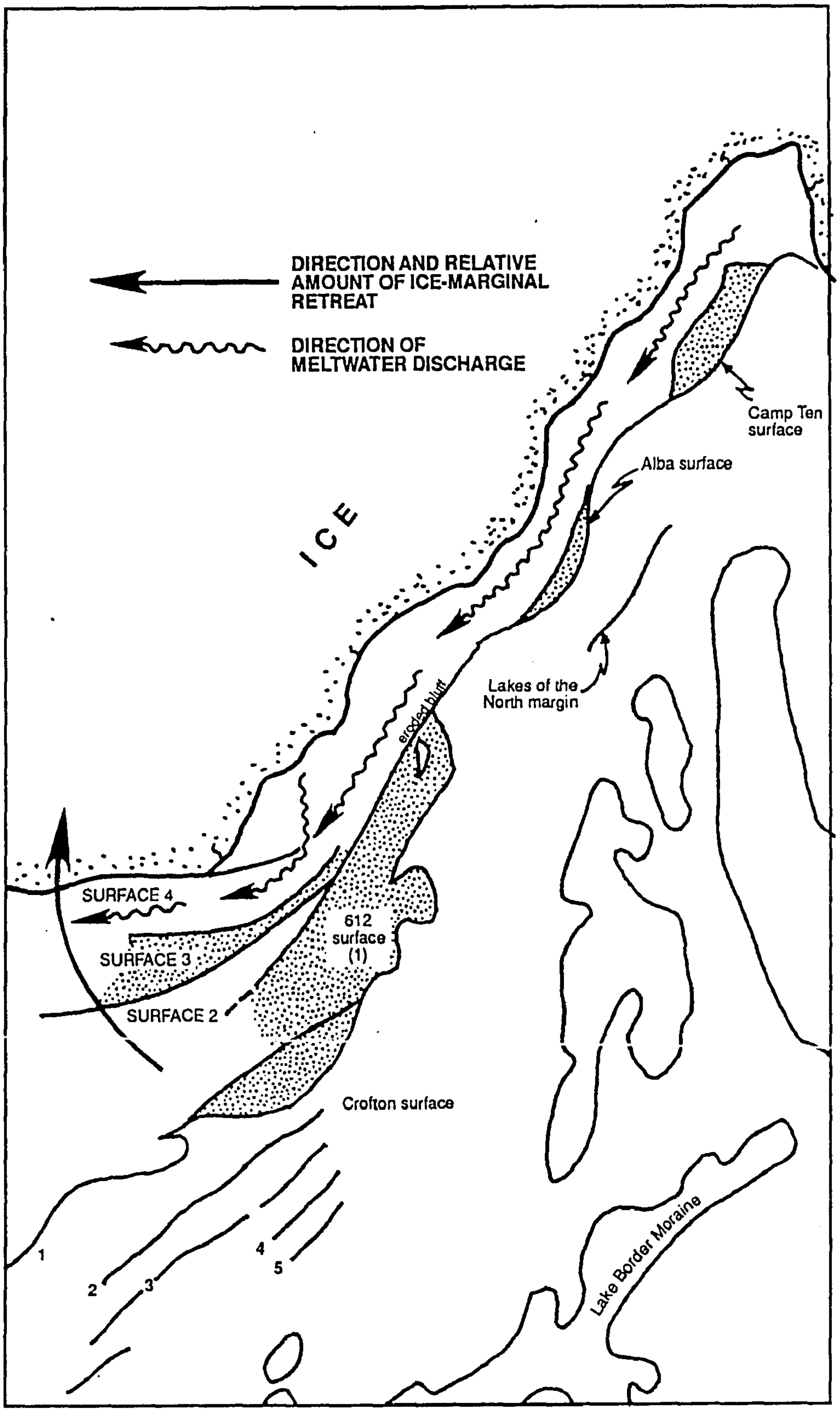

Figure 46. Formation of surfaces 3 and 4.

46). Such a pattern is consistent with interpretations from the Outer Port Huron feature, where southern terminii likewise pivoted northwestward. Interestingly, Burgis (1977) found that Port Huron deglaciation in northeastern southern Michigan progressed from south to north in a similar fashion, except there the ice margin rotated northeastward.

The Hoffman Lake Channel, located at the Inner Port Huron apex, is cut deeply into the Elmira Plain, yet this latter surface is not incised immediately to the south. If an ice margin was positioned along the ice-contact slope at these two locations contemporaneously, then the associated meltwater would have incised the Elmira surface at both places. This suggests that ice remained at the apex after areas farther south were already deglaciated (Fig. 47). Because meltwater in the Hoffman Lake Channel drained eastward, the area to the east must have been ice free. Thus, the Hoffman Lake Channel formed after formation of the Elmira surface and deglaciation of the apex's eastern side, but before retreat from the western edge (Fig. 47).

On these bases, the Hoffman Lake feature is interpreted as having formed very late in the Inner Port Huron deglaciation sequence. Burgis (1977), studying the Port Huron Moraine in northeastern Michigan, also concluded that the Inner Port Huron apex was the last region to be deglaciated during Port Huron retreat.

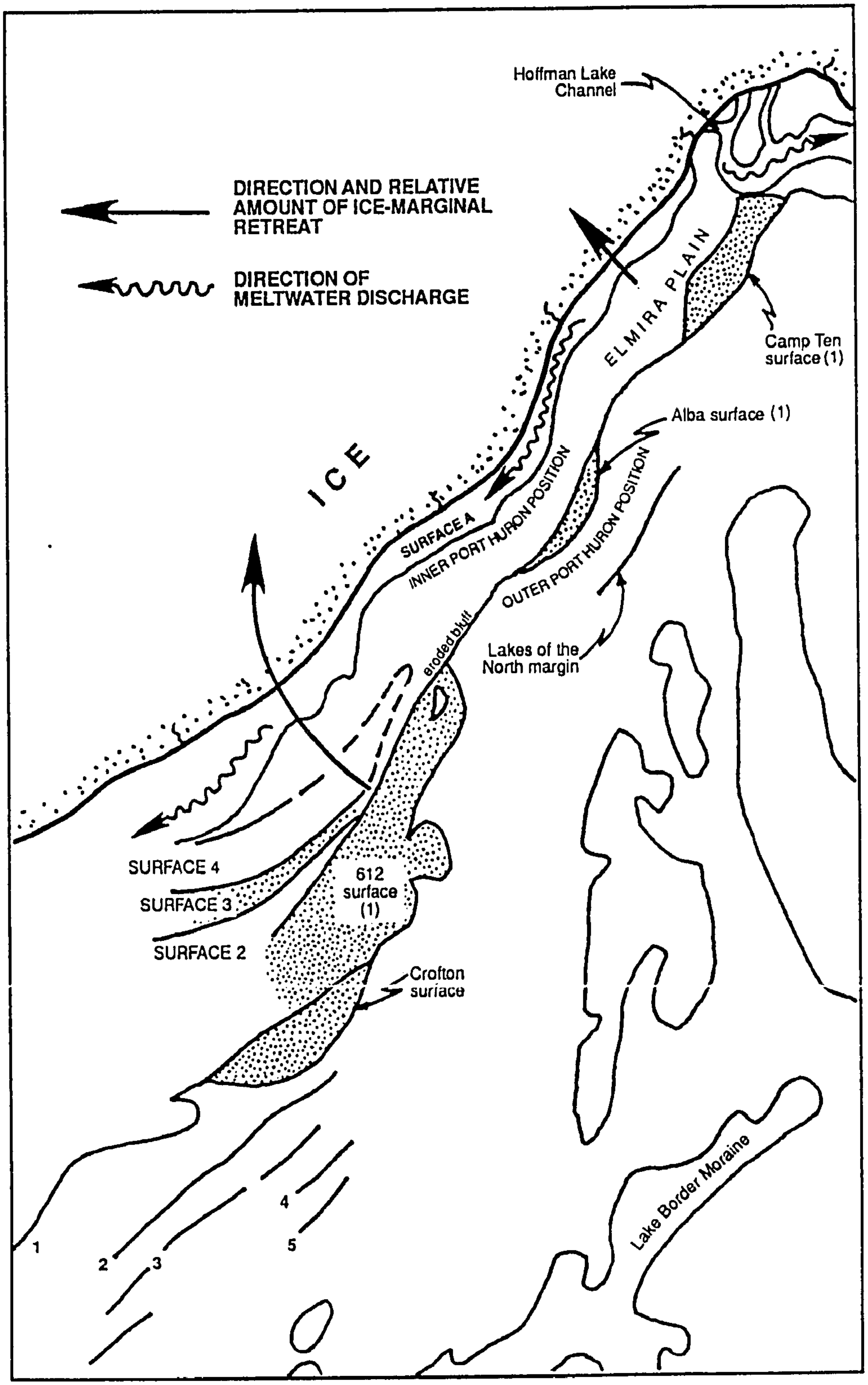

Figure 47. Formation of surface A.

There is the possibility that the Hoffman Lake Channel formed from drainage of Greatlakean/Valderan ice that had readvanced to positions marked by the apex. Melhorn (1954) and Burgis (1977), however, both map the Greatlakean/Valderan boundary north of the apex, suggesting that this advance did not reach the proximal border of the Inner Port Huron Complex here.

Phase 4

As the margin withdrew from the Inner Port Huron position, proglacial lakes formed proximal to the Inner Port Huron ice-contact slope. Organic material from sediments associated with one of these lakes yielded a ^{14}C age estimate of 12,960 ± 350 yrs. B.P. (TX-6151; Antrim County Road Commission Gravel Pit), and indicates that the ice margin was proximal to the Inner Port Huron Complex at this time.

With continued retreat, a succession of lower outwash surfaces (A-H, W-Z) were formed, beginning with surface A (Fig. 47) and followed by incision of surfaces B, C, and D. Together with terraces E-H2 and W-Z, they record the transition from a single, meltwater dominated braided channel to two separate precipitation/groundwater controlled single channel systems (Cedar-Green and Jordan-Warner valleys; Fig. 48).

Surface A is closely related to surfaces 1 and 2 (Elmira Plain). All are extensive, regionally significant depositional features containing thick

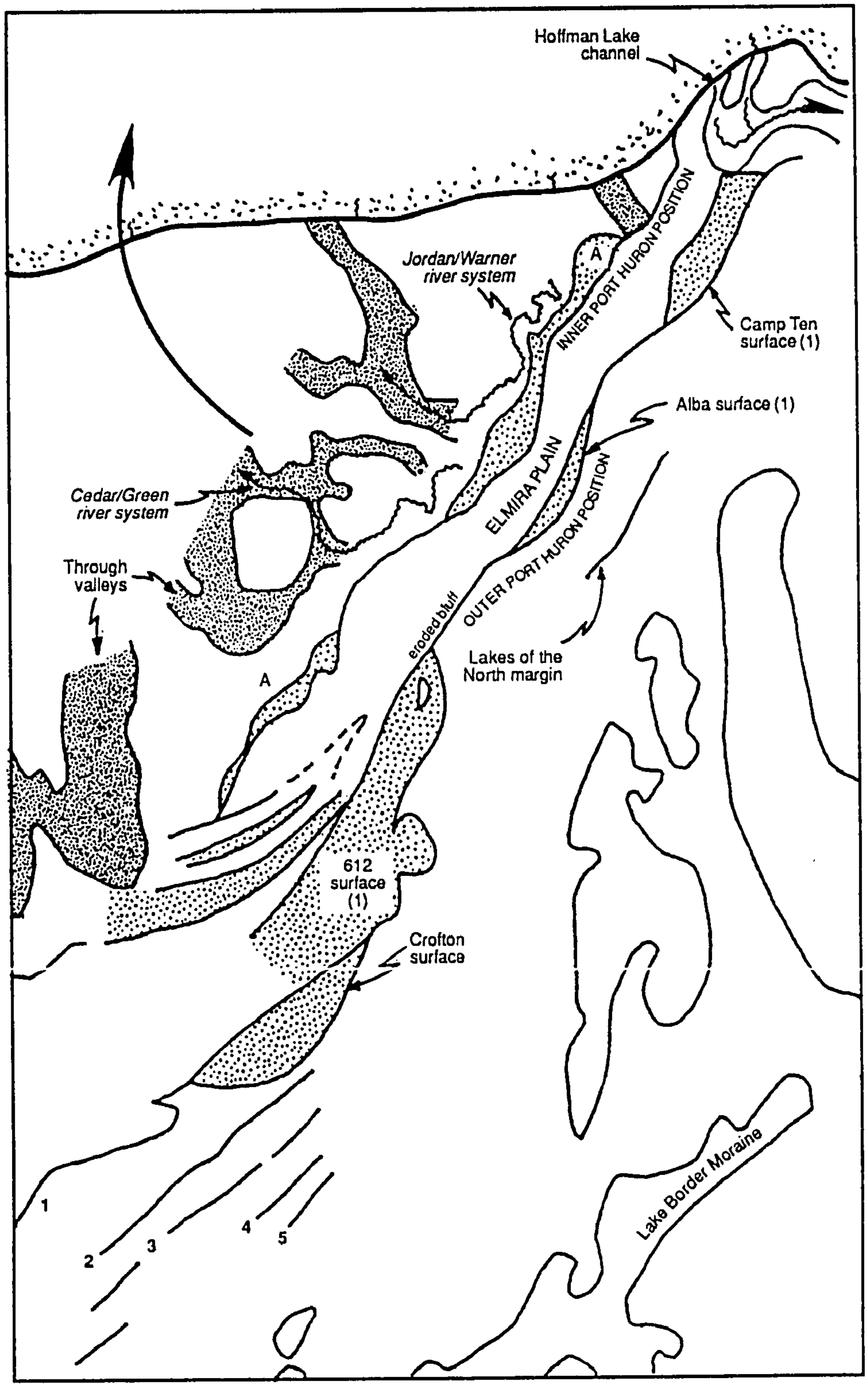

Figure 48. Formation of the Jordan-Warner and Cedar-Green river systems.

outwash deposits formed along a relatively stable ice margin. In striking contrast, lower terraces are much smaller features. They represent a comparatively brief deglaciation interval characterized by falling base levels caused by opening of lower outlets, with a concomitant drop in water tables. Relationships here are very complicated because of the 1) paucity of terrace remnants, 2) poor chronologic control on fluvial and glaciofluvial surfaces, 3) limited knowledge of related lake levels in the Lake Michigan basin and 4) uncertain role (if any) of Greatlakean/Valderan ice in stream history.

Phase 5

Sometime after formation of the Post Inner Port Huron position (perhaps during the subsequent Greatlakean/Valderan advance) the ice margin in places readvanced to the Inner Port Huron crest. As noted in Chapter 4, downstream portions of surfaces 3, 4, and 5, along with parts of the Post Inner Port Huron zone, were overridden by ice and then buried by stagnation deposits in secs. 35 and 36, T. 28 N., R. 8 W., and secs. 1 and 2, T. 27 N., R. 8 W. (Fig. 49). Evidence for burial includes 1) an abrupt downstream termination of wide, gently sloping, low relief outwash surfaces by uncontrolled disintegration topography, and 2) altitudes within these disintegration tracts that are much too high to correlate with surfaces 3, 4, or 5. Burial must post-

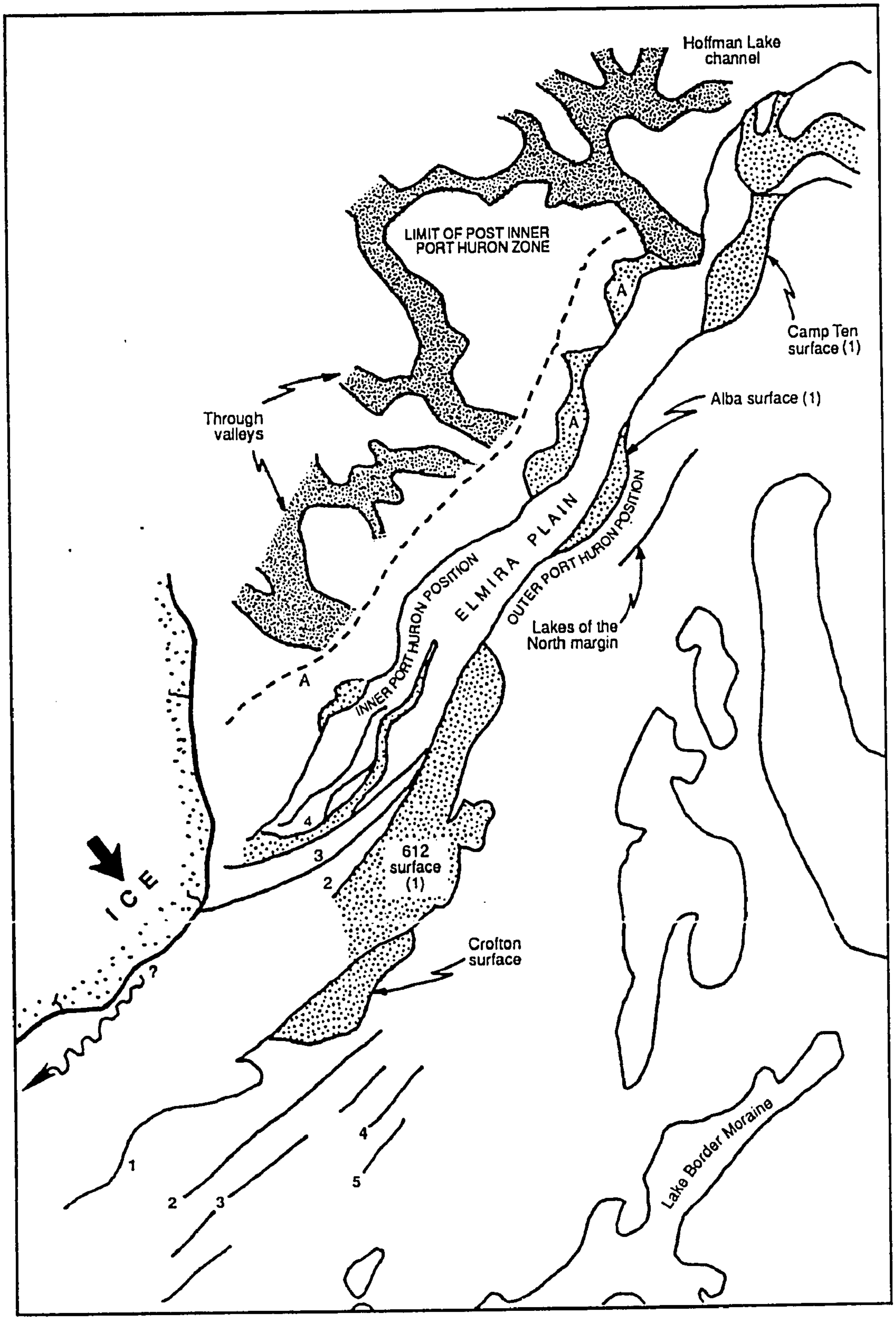

Figure 49. Readvance after formation of the Post Inner Port Huron zone.

date Phase 3 and 4 and reflects either 1) ice-marginal flucuations during final Port Huron deglaciation, or 2) Greatlakean/Valderan advance (Fig. 49).

Phase 6

Topography in the study area has experienced little Holocene alteration, due in part to the highly permeable sandy drift which limits runoff favoring the formation of integrated drainage networks. An important exception exists at the Alba salient, where a flat bottomed, 15 m deep, dry channel with numerous tributary valleys trends westward from the Outer Port Huron Complex down to the Elmira Plain. The orientation of the lowland and lack of an associated hanging valley at its upstream end precludes a superglacial meltwater source. No spring or evidence for spring sapping is observed. This valley likely formed immediately following deglaciation, when water tables were much higher, providing large amounts of effluent to this stream system. As ice withdrew, water tables dropped, perhaps precipitously, accompanied by a brief period of incision by these streams. Elsewhere, this process produced only limited dissection along the Outer Port Huron margin and surface 1 terrace scarps.

West of Alba, a spectacular example of spring-sapping in lacustrine (?) clay is observed at the Landslide Creek overlook. Here, an ampitheater-like hollow, concave to the west and more than 50 m deep, forms the headwater region of Landslide Creek. This feature is the most conspicuous example of the widespread Holocene spring-sapping occurring throughout tracts proximal to the Inner Port Huron Complex.

Stream piracy, augmented by spring-sapping, is an important process in the Cedar-Green and Jordan-Warner Creek systems, where streams cutting headward into the Inner Port Huron slope have produced a complicated sequence of Holocene drainage diversions. This is best displayed in secs. 27 and 28, T. 30 N., R. 6 W., where headward portions of the Cedar River (oriented parallel to the Inner Port Huron bluff) have been captured by Green River and Cascade Creek (oriented perpendicular to the Inner Port Huron slope). These latter, higher gradient stream networks may be expected to expand at the expense of lower gradient streams in areas proximal to the Inner Port Huron ice-contact slope.

Regional correlation

In 1905 Taylor proposed that the Port Huron Moraine marks the outer limits of a significant glacial advance, his evidence based primarily on the relationship of the moraine to beaches of glacial lakes Arkona and Whittlesey. This interpretation postulated that a low-altitude glacial lake, Lake Arkona, occupied the southern part of the Lake Huron basin prior to formation of the Port Huron Moraine. Advance of Port Huron ice into southeastern Michigan ponded the waters of Lake Arkona and formed a new, higher altitude lake, Lake Whittlesey. Taylor (1905) documented truncation of Lake Arkona beach features by the moraine and showed that Lake Whittlesey was penecontemporaneous with the Port Huron feature.

Modern studies confirm Taylor's interpretations (Fullerton, 1980). Age determinations associated with the rise and stabilization of Lake Whittlesey in Ontario and Ohio yield ^{14}C ages of 12,920 ± 400 (W-430; Goldthwait, 1958), 12,900 ± 200 (I-3175; Calkin, 1970), and 12,800 ± 250 (Y-240; Barendsen, Deevey, and Gralenski (1957). Based on some of these dates, Hough (1958) assigned an age of 13,000 yrs. B.P. to the Port Huron advance in the Great Lakes region.

Taylor (1913) correlated the Port Huron Moraine in southeastern Michigan with the Wyoming Moraine in southwestern Ontario. Wood associated with St. Joseph till from the Wyoming Moraine yielded a ^{14}C age estimate of 13,000 ± 100 yrs. B.P. (GSC-2213; Gravenor and Stupavsky, 1976; Lowdon and Blake, 1976). Eschman correlates this till with "Jeddo till" from the Port Huron Moraine:

> It seems certain that the Jeddo till is the Michigan equivalent of the St. Joseph till of Ontario -- each is the surface till in the terminal morainic system of Port Huron age, and that system has only a relatively narrow gap in it in the Port Huron - Sarnia region (Eschman, 1978, p. 37).

Thus, the age of the Port Huron Moraine in southeastern Michigan is based on ^{14}C dates associated with morphologic and stratigraphic units from outside of the state that apparently correlate with the feature's type area.

<u>Correlation within Michigan</u> -- Taylor (1899, plate II) presented the first map linking the Port Huron Moraine to topographic features in the northern part of the Southern Peninsula. Leverett's 1911 map of the surficial formations shows the Port Huron Moraine trending from its type area near Port Huron northwestward to Muskegon. Description, correlation, and interpretation of the feature within Michigan was published by Leverett and Taylor in 1915.

Blewett (1989) reviewed the basis for this correlation and identified four principal criteria used by Leverett and Taylor:

1. PATTERN -- the moraine (as mapped by Leverett) is nearly continuous across the state.

2. FORM -- the moraine is a conspicuous topographic feature, high and rugged in some areas, low and subdued in others

3. ASSOCIATION --

   a. the moraine lies "inside" of the older West Branch-Lake Border Complex;

   b. the moraine is discordant with the West Branch - Lake Border Complex;

   c. the moraine buries Lake Arkona beaches in southeastern Michigan;

   d. the moraine is coeval with beaches of Lake Whittlesey;

   e. near Lake Michigan the moraine is related to lakes deemed correlative with Port Huron events in the Huron-Erie basins.

4. LITHOLOGY -- the moraine is delineated using fine textured sediments in the Saginaw lowland.

Based on newly available topographic quadrangles, soil maps, and aerial photographs, Blewett (1989) recognized five subunits within the moraine that differed sharply in morphologic and sedimentologic characteristics, and observed that Leverett and Taylor's correlations, though generally accurate, can be questioned in some places. These areas include 1) northeastern southern Michigan, where the feature is not continuous, and 2) the Saginaw lowland, where morainic topography is poorly developed. Blewett's analysis concluded that age estimates and correlation of sediments and terrain in northwestern southern Michigan would likely be established on the basis of appropriate ^{14}C dating. Until the present study, however, age estimates for Late Wisconsinan organic deposits in the northern part of the Southern Peninsula were limited to Farrand et al. (1969; see next section).

<u>Age determinations for the Port Huron Complex in northern Michigan</u> -- Organic material was recovered from a lacustrine silt deposited immediately proximal to the Inner Port Huron Complex, about 50 m below the crest (Antrim County Road Commission gravel pit, hereafter "Antrim County" site; NW 1/4, NW1/4, sec. 33, T. 30 N., R. 6 W.). This material yielded a ^{14}C age estimate of 12,960 $\pm$ 350 yrs. B.P. (TX-6151). Because the lake

associated with these deposits formed in a narrow zone between the Inner Port Huron ice-contact slope and an ice margin located less than a kilometer to the northwest, the silts must postdate the Inner Port Huron Complex. The age and location of these sediments mean that the Inner Port Huron Complex within the study area likely formed prior to 12,960 ± 350 yrs. B.P. and establishes a minimum age estimate for the feature. An alternative interpretation, that these deposits continue beneath the Inner Port Huron Complex and predate the feature, is not likely because data from numerous wells drilled along the Inner Port Huron crest (Elmira surface) show sand and gravel, rather than clay, at comparable altitudes.

The older Lake Border Moraine is located southeast of the Port Huron Complex in northwestern southern Michigan, and can be traced southward into northern Illinois. Fullerton (1980) assigned an age of 14,200 - 14,300 yrs. B.P. to the complex, an interpretation supported by recent ^{14}C dates (13,870 ± 170 and 14,100 ± 640 yrs. B.P.; ISGS-1549 and ISGS-1570; C.L. Lin, 1987; cited in Hansel and Mickelson, 1987) associated with the Glenwood I stage of Lake Chicago, which formed soon after ice marginal retreat from the Lake Border Moraine in Illinois (Fullerton, 1980). Based on these estimates, the Lake Border Moraine provides a maximum age of approximately 14,000 yrs. B.P. for the Port Huron Complex in northwestern southern Michigan, and, combined with the Antrim County date, indicates that the Inner and Outer

Port Huron Complexes formed between approximately 13,000 and 14,000 yrs. B.P.

Farrand et al. (1969) describe a buried bryophyte bed buried by a single red till near Cheboygan, Michigan, that apparently marks a short ice-free interval defined by three dates (13,300 ± 400 and 12,800 ± 400, L-1064; 12,570 ± 500, W-1889; and 12,500 ± 500, W-1847). Three other ages from the same bed (Crane and Griffen, 1968) are 9,960 ± 350 (M-1753-1), 10,700 ± 350 (M1753-2), and 10,700 ± 350 (M-1753-3). The first date was rejected by Farrand et al. as being too young; the other two were not mentioned. Based on a complicated set of assumptions predicated by acceptance of the older dates, the bryophyte bed was assumed to represent an ice-free interval lasting from about 13,000 to 12,500 yrs. B.P., that immediately pre-dated the Port Huron advance; it has been named the Cary-Port Huron interstade. The till overlying the bryophyte bed was interpreted to represent uninterrupted deposition of till during both the Port Huron and Greatlakean/Valderan substages. In other words, according to Farrand et al. 1) the bryophytes were buried by red till during Port Huron advance to the maximum Port Huron position, 2) the ice margin subsequently retreated during Two Creeks time, but not far enough north to uncover the bryophyte region, and 3) Greatlakean ice then readvanced, followed by final deglaciation of the Southern Peninsula.

Farrand's bryophyte bed (now covered) is located approximately 75 km northeast of the Antrim County site. Because the Inner and Outer Port Huron Complexes must have formed between 13,000 and 14,000 yrs. B.P., estimates of 12,500 - 13,000 yrs. B.P. from the Cheboygan site are too young to be easily accomodated.

Fullerton (1980) reevaluated Farrand's interpretation and believes the deposit may correlate with the Two Creeks buried forest in Wisconsin (numerous dates averaging about 11,850 yrs. B.P.; Black and Rubin, 1967-1968):

> In view of (1) the uncertain reliability of correlation by means of pollen spectra, (2) the 3,700-year range of measured ages of the Cheboygan bed, (3) the age discrepencies in dating the Castalia bryophytes, and (4) the possibility of isotope fractionation in some species of bryophytes, the age and correlation of the Cheboygan bed are considered unproved. Resolution of the age of the bed is extremely important because the deglaciation history in the Lake Michigan and Lake Huron basins is dependent upon assignment of a correct age to the bryophyte bed...(Fullerton, 1980, p. 20).

In light of these criticisms, determining the maximum age of the Port Huron advance in Cheboygan County on the basis of Farrand's bryophyte site is questionable, especially given the overlap between the Antrim County and Cheboygan age determinations. Because the Antrim County estimate records deglaciation of the Inner Port Huron Complex, Farrand's bryophyte dates (if they are correct) may instead record the beginning of a Two Creeks (Fullerton, 1980), rather than a Cary-Port Huron, ice-free interval. If so, the till overlying the bed is Greatlakean/Valderan in age rather than a continuous deposit spanning both Port Huron and Greatlakean/Valderan time. Indeed, the 1) strong agreement among Antrim County (this study), Ontario (Gravenor and Stupavsky, 1976), and Ohio (Barendsen et al. 1957) radiocarbon dates for the Port Huron Moraine and Lake Whittlesey, plus 2) the overall accuracy of morphologic correlation between the Antrim County site and the type Port Huron area (Blewett, 1989), indicates that the Antrim County age estimate may be a more reliable basis for determining Port Huron chronologies in northern Michigan than the bryophyte site. It also provides, for the first time, a minimum age estimate for the Port Huron advance in this part of the state.

<u>Conclusions</u> -- Prior to this study, correlation of the Inner and Outer Port Huron Complexes with the type Port Huron Moraine in southeastern Michigan was based primarily on morphology. Similarily, the latter feature was correlated with the Wyoming Moraine in southwestern Ontario, and both were deemed coeval with Lake Whittlesey landforms and sediments throughout the Erie basin. Because age determinations were not available for the Port Huron Complex within Michigan before the report by Farrand et al. (1969), radiocarbon age estimates from Ontario and Ohio were assigned to the Port Huron type area based on these morphologic correlations, and, at the same time, applied to the Port Huron Complex throughout

Michigan. Thus, following a rather circuitous route, the Port Huron Complex in northern Michigan was assumed (but not verified) to be about 13,000 radiocarbon years old.

This study presents a minimum radiocarbon age of 12,960 ± 350 yrs. B.P. for the Inner Port Huron Complex in northwestern southern Michigan and, given the controversy surrounding the Cheboygan bryophyte age estimates, provides a reliable basis for establishing a minimum age for the Port Huron Complex in the northern part of the Southern Peninsula. This age determination 1) agrees with ^{14}C dates from the Wyoming Moraine in Ontario and with dates associated with Lake Whittlesey in Ohio, 2) helps verify Leverett and Taylor's correlation of the Port Huron Complex across the Southern Peninsula, and 3) for the first time, establishes a minimum age for the Port Huron Complex within Michigan.

Chapter 5

CONCLUSIONS AND IMPLICATIONS

This chapter summarizes the sedimentologic, morphologic, and chronologic findings of this study as they relate to the Inner and Outer Port Huron complexes in northwestern southern Michigan. Sediments are discussed based on their vertical and horizontal aspects. Landforms are presented in order of decreasing size.

Sedimentologic findings

Surficial sediments of the Inner and Outer Port Huron Complexes are almost exclusively 1) glaciofluvial sand and gravel, and 2) glaciolacustrine silt and clay. Till is almost wholly restricted to the fluted uplands and the Post Inner Port Huron zone. Crestal areas exhibit ice-contact stratified drift and surficial boulders associated with deposition along marginally stagnant ice. This evidence, along with the presence of hummocky topography, indicates that in many areas outwash deposition began in the stagnant zone up-ice from the margin and extended southeastward beyond the ice terminus.

Meltwater deposition and erosion were the dominant geomorphic processes operating in the study area during deglaciation. Variable aspects of glaciofluvial deposition are clearly revealed at nine gravel pits located on the Elmira Plain. Comparisons of sediment texture and diagnostic bedform lithofacies show a transition from coarse, poorly sorted, proximal deposits dominated by longitudinal bars, to distal fine textured, well-sorted braided stream deposits displaying sandy bedforms. Paleocurrent indicators show that meltwater streams first flowed perpendicularly away from the ice margin and then turned 90 degrees to the right to flow parallel to the sandur axis. Conservative paleodischarge estimates are 415-915 $m^3 sec^{-1}$, comparable to those from other sandur studies.

On all these bases, proximal surficial sediments of the Inner and Outer Port Huron Complexes in the study area are interpreted to be proglacial and ice-contact stratified drift. These sediments are not "coarse-textured glacial till" as mapped by others (Farrand and Bell, 1982), but, instead are proximal facies of especially important heads of outwash graded to the Elmira and Outer Port Huron outwash plains.

Data from water and petroleum well logs indicate that the Inner and Outer Port Huron features each contain an uppermost wedge of sand and gravel up to 80 m thick, deposited on a moderate relief till surface inclined to the northwest. The uppermost sand and gravel units were likely formed by infilling along a quasi-stable, marginally stagnant glacial position in some areas, and in others by deposition along a steadily retreating ice margin.

Morphologic findings

Overall, the terrain of both the Inner and Outer Port Huron Complexes display a distinct pattern of salients and reentrants. The location and size of the various salients is closely related to the magnitude of lower areas on the deeply buried bedrock surface. Salients, like their associated bedrock lowlands, are progressively larger southward, beginning with the small Elmira and Alba features in the north, followed by the larger Kalkaska salient paralleling Grand Traverse Bay, and culminating in a broad 150 km-wide salient (located outside of the study area) paralleling Lake Michigan from Grand Traverse County southwestward to Whitehall.

Northern and southern sections of the study area show strong contrasting relationships among bedrock form, drift thickness, and the modern landscape. In the north, the topography appears to be influenced by high bedrock surface relief combined with relatively thin drift. Southward, where drift is thicker and bedrock relief lower, this relationship is absent. Interestingly, the latter area coincides with the broad Kalkaska salient and its associated extensive bedrock low. This suggests that glacial dynamics related to thicker, faster ice flowing from the Grand Traverse Bay lowland may help explain the relationships observed.

Twenty-six separate surfaces are recognized within the Mancelona Plain and Post Inner Port Huron zone; these can be grouped into four categories:

1. Extensive surfaces representing thick outwash deposits that formed along quasi-stable ice marginal positions of relatively long duration (surfaces A, 1, and 2, plus the Crofton terrace).

2. Less extensive surfaces 3-8, recording a brief interval of falling base levels caused by opening of lower outlets and concomitant drops in the water table during deglaciation.

3. Surfaces B-Z, marking the Pleistocene-Holocene transition in the Cedar-Green and Jordan-Warner river systems.

4. The Hoffman Lake Channel, recording incision of the Elmira surface, and deglaciation of the eastern side of the Inner Port Huron apex.

Character and distribution of some of these surfaces is related to the regional salient and reentrant pattern discussed earlier. Terraces are preferentially preserved in salient regions, with larger salients containing larger terrace remnants. Altogether, these surfaces record long intervals of quasi-stable ice-marginal conditions favoring thick outwash deposition, punctuated by brief transitional periods of rapid incision as the ice margin retreated.

In addition to the larger features described above, numerous smaller landforms are associated with hummocky proximal tracts of the Inner and Outer Port Huron Complexes. These include hanging valleys, perched fans, disintegration ridges, and ice block depressions. All are evidence for the presence of stagnant ice.

Morphologic and sedimentologic evidence indicates that deglaciation in the south was characterized by a series of successive ice marginal positions, younger to the northwest, followed by readvance and burial of some areas by 1) flucuations of the glacial terminus during Port Huron retreat, or 2) Greatlakean/Valderan advance. The 1) presence of multiple ice margins in southern sections of the Outer Port Huron Complex, 2) location of the Crofton surface relative to these latter features, 3) apparent gradation of small incised valleys formed at the Inner Port Huron position to lower surfaces found proximal to this same margin farther south, and 4) incision of the Hoffman Lake Channel in the apex region, with an absence of similar downcutting immediately southward, all support the interpretation that the ice terminus pivoted clockwise to the northwest during deglaciation.

Although deglaciation was complex and far from uniform, six lines of evidence indicate that progressive stagnation formed at least 9 morphosequences (Margins 1-5, the Lakes of the North, surface 1, Inner Port Huron, and Post Inner Port Huron positions). First, the existence of numerous ice-contact slopes and ice-contact landforms are all evidence for the presence of stagnant ice. Second, because surfaces consistently slope southeast or southwest, the morphology, orientation, and spatial arrangement of outwash features indicate formation in association with a stagnant glacial margin rather than isolated blocks of dead ice. Third, surficial sediments of the study area are primarily outwash sand and gravel that exhibit a facies change which fines distal to the head of outwash. Fourth, profiles constructed across the area show the characteristic imbricate-like pattern delineating morphosequences. Fifth, topographic maps indicate a transition from more collapsed to less collapsed terrain distally from heads of outwash. Finally, morphosequences are controlled by a specific base level. Outwash surfaces of the Inner and Outer Port Huron Complexes apparently are graded to the Glenwood II stage of Lake Chicago (Burgis, 1977); terraces in the Post Inner Port Huron zone may be graded to lower base levels. All of the above characteristics are listed by Koteff (1974, p. 121) as criteria for identification of morphosequences.

The 1) overwhelming importance of glaciofluvial deposition and sediments, 2) lack of significant amounts of till, and 3) presence of numerous alluvial fan-like profiles, ice-contact slopes, hanging valleys, perched fans and disintegration ridges indicate that the Inner and Outer Port Huron Complexes are not classic end moraines, but instead mark terrain formed in association with abundant meltwater and stagnant ice during final deglaciation. Areas mapped as end moraine by others (Martin, 1955; Farrand and Bell, 1982) are actually hummocky proximal topography associated with two especially prominent and important heads of outwash graded to their respective outwash plains.

Chronologic findings

Organic material from lacustrine deposits located proximal to the Inner Port Huron slope (Antrim County site) yield a ^{14}C age determination of 12,960 ± 350 yrs. B.P., and provide a minimum date for the Inner and Outer Port Huron complexes in the study area. The nearby Lake Border Complex with an age of approximately 14,000 yrs. B.P., combined with the Antrim County date, indicates that the Port Huron complexes probably formed between about 13,000 and 14,000 yrs. B.P. Controversial dates associated with the Cheboygan bryophyte bed (12,500 - 13,000 yrs. B.P.) are too young to mark an ice-free interval prior to the Port Huron advance, but may mark the beginning of the Two Creeks interstade. The Antrim County age determination 1) agrees with estimates for correlatives of the Port Huron Moraine in Ohio and Ontario (Barendsen et al., 1957; Gravenor and Stupavsky, 1976), 2) helps verify correlation of the Port Huron Complex within Michigan (Leverett and Taylor, 1915; Blewett, 1989), and 3) for the first time, provides a minimum age on the Port Huron advance in the northwestern part of the Southern Peninsula.

Suggestions for further research

During the course of this investigation it became clear that four topics warrant additional consideration. (1) Tracing the Elmira Plain southwestward to the Glenwood shoreline may establish precise relationships between the Inner Port Huron Complex and Lake Chicago, and also help in interpreting the complicated assemblage of glacial landforms in Grand Traverse, Wexford, Benzie, and Manistee Counties. (2) Drainage evolution in the area is complex, poorly understood, and warrants investigation. A detailed analysis of relationships among fluvial terraces, Holocene lake levels, river gradients, and stream patterns and piracies might provide valuable insights into Quaternary landscape development. (3) The deglaciation chronology in northwestern southern Michigan will remain incomplete until there is a full and accurate understanding of Greatlakean/Valderan events. Detailed field study in the area where surfaces 3, 4, and 5 are buried by deposits from a minor readvance, may reveal key morphologic and stratigraphic relationships which are important in this research. Distinguishing between the Manistee and Inner Port Huron Complexes (if two features exist) to the south will likely be central to any such study. (4) The character of the Port Huron Complex both to the east and southwest of the study area is poorly understood; investigating the changing modes of deposition along the feature might provide a better understanding of glacial landforms in this part of Michigan.

Finally, this and other recent studies including Rieck (1976), Burgis (1977), and Blewett and Rieck (1987) demonstrate the usefulness of research on regional geomorphology in understanding Michigan's glacial landscape. Unfortunately, very few reports have been published since Leverett and Taylor's 1915 monograph and little detailed mapping has been done. An accurate understanding of glacial sediments is especially important given recent concerns regarding groundwater contamination and hazardous waste disposal. Michigan is far behind adjoining states and Ontario in documenting and interpreting its Quaternary sediments and landforms. A regional mapping program, funded by the Department of Natural Resources' Geological Survey Division or the U.S. Geological Survey would be a major first step in addressing these inadequacies.

APPENDICES

APPENDIX A

FIELD AND LABORATORY TECHNIQUES

FIELD TECHNIQUES

GRAVEL PITS AND OTHER EXPOSURES

Nine gravel pits containing fresh vertical faces at least 3 m high and 3 m wide were sampled using the techniques described below:

Sand and gravel --

1. Four locations within each pit were chosen at random using a board game spinner.

2. An excavation approximately one meter long by two meters high was made 1.5 m below the top of the face at each of the four sites. Absence or presence of bedding was recorded, as were details of sediment type and stratigraphic association.

3. A two meter vertical sample (Krumbein and Pettijohn, 1938) was taken and dumped at a predetermined collecting area.

4. Subsamples from all four areas were mixed together at the collection site and together formed the main sample for that site.

5. Fine textured sediments ($<$ 8 mm) were collected by ten random hand grabs and labeled for later sieving in the laboratory.

6. Seventy-five coarse ($>$8 mm) fragments were sampled using a wire grid placed atop the collecting pile.

7. Principal axis lengths (in cm) were measured and recorded for later texture analysis and sphericity study. Roundness was determined visually using a standard set of grain images (Leeder, 1982).

8. Clasts were then classified based on lithology. Those rocks of unknown origin were collected for laboratory study.

In addition, orientation of imbricated stones was measured in order to determine paleocurrents. These measurements were taken where orientation was best developed or where the face of the exposure was most accessible. Orientation and dip of 50 elongated clasts (3:1 a-b ratio, minimum a-axis length 1 cm) were recorded.

Till -- Identifiable tills were sampled from at least three places within the till mass and mixed together to form a sample. Two such samples were collected and tagged for later analysis in the laboratory.

SURFICIAL SEDIMENT STUDY

Surficial sediment study consisted of 1) boulder mapping, and 2) sampling of field stone piles.

Boulders -- Based on road reconnaissance, places where three or more boulders ≥50 cm in b-diameter exist within 100-150 meters of one another were recorded, as were lithology and overall shape (angular, sub-angular, round). Ornamental boulders or those of questionable origin were not included.

Field stone piles -- All recognizable stone piles (as determined from road reconnaissance) were sampled using the following methodology:

1. Two separate points within a stone pile were chosen at random using a spinner.

2. A rectangular grid was centered over each point and 25 stones collected.

3. Stones from the two sites were then mixed together to form a sample of 50 stones.

4. Principal axes, roundness, and lithology of individual stones were determined in the field. Stones of unknown lithology were brought to the lab for further analysis.

LABORATORY TECHNIQUES

SAND AND GRAVEL

Fine textured material (<8 mm) -- Sieving follows the standard methodology described by Krumbein and Pettijohn (1938) and by Folk (1974) but differs in that coarsest fragments (>8 mm) were measured in the field based on the methodology already discussed. This method avoids the large sample sizes otherwise required due to the coarseness of the material.

Fine textured samples (<8 mm) were divided into two subsamples, one serving as backup. 70 grams of the main sample were weighed and separated using nested sieves following standard procedures. Each separate was then weighed and a relative percentage for each category calculated.

Sphericity -- Sphericity measures relative compactness of a rock and is an indirect measure of mechanical wear upon a rock fragment. This study follows Church (1972) and uses the following measure:

$S = \sqrt[3]{bc/a^2}$ (Krumbein's intercept sphericity) where a, b, and c are principal axes and S = sphericity. Values from each location were mapped to determine spatial variability across the sandur.

TILL

Texture -- Till was separated into coarse and fine fractions using a 2 mm sieve. Fine textured material was then analyzed by hydrometer based on the following method (Indorante, et al., 1990):

1. A 50 gram sample was placed in a fleaker, oven dried, dessicated, cooled and reweighed.

2. Ten ml of 5% sodium hexametaphosphate was added to the fleaker. The fleaker was then filled to 1/3 to 1/2 full.

3. The fleaker was capped and put in a shaker for 12 hours at low to medium speed.

4. The soil/liquid mixture in the fleaker was washed into and through a 53 um sieve into a 1000 ml settling cylinder.

5. Sand in the 53 um sieve was washed into a beaker and oven dried. This sample was cooled, dessicated, and weighed.

6. The settling cylinder was filled with distilled water to the 1000 ml mark and placed in a temperature controlled room overnight.

7. The mixture in the cylinder was then agitated for 30 seconds.

8. The material in suspension was then measured using a hydrometer. Times for hydrometer readings were determined based on temperature. Readings were taken for each sample as well as for a blank.

9. Percentages of sand, silt and clay were then determined for each sample.

Color -- Color of moist and dry samples were recorded for each sample using Munsell color charts.

APPENDIX B

CLAY MINEROLOGY

Minerology of tills was examined using X-ray diffraction of oriented clay (Fig. 50), following Glass (no date). Samples were scanned at 30 KV and 15 milliamps between 5-14 degrees 2 theta at a scan rate of 1 degree per minute. Peak and background counts were calculated by computer. Each of the 11 till samples were run in triplicate. Preparation procedures are described below:

1. Twenty-five grams of sample were added to a 300 ml fleaker and topped out with approximately 150 ml of distilled water.

2. The fleaker (with cap on) was shaken vigorously by hand for 1 minute.

3. In one quick motion approximately 100 ml of the mixture was poured into a 100 ml beaker and the remainder of the soil/water suspension was discarded.

4. The beaker was covered and allowed to sit overnight to allow flocculation.

5. If the clear supernatant was distinguishable the next day, it was siphoned off and the beaker was refilled with distilled water, vigorously stirred for one minute with a clean glass rod, and allowed to sit overnight again. This was repeated until the supernatant remained somewhat cloudy after 24 hours. One third of the solution was then siphoned off and the beaker topped off with distilled water.

6. Two drops of a 10% Calgon solution were added to the beaker.

7. The solution was hand mixed for 1 minute with a stirring rod and then allowed to stand for 15 minutes.

8. An eye-dropper full of solution was drawn off (as much as possible in one motion) from the top of the solution and applied to glass petrographic slides. The whole slide was covered by spreading out the liquid with the top of the dropper and the slide was kept level throughout the process.

9. The slide was allowed to dry at room temperature for one day.

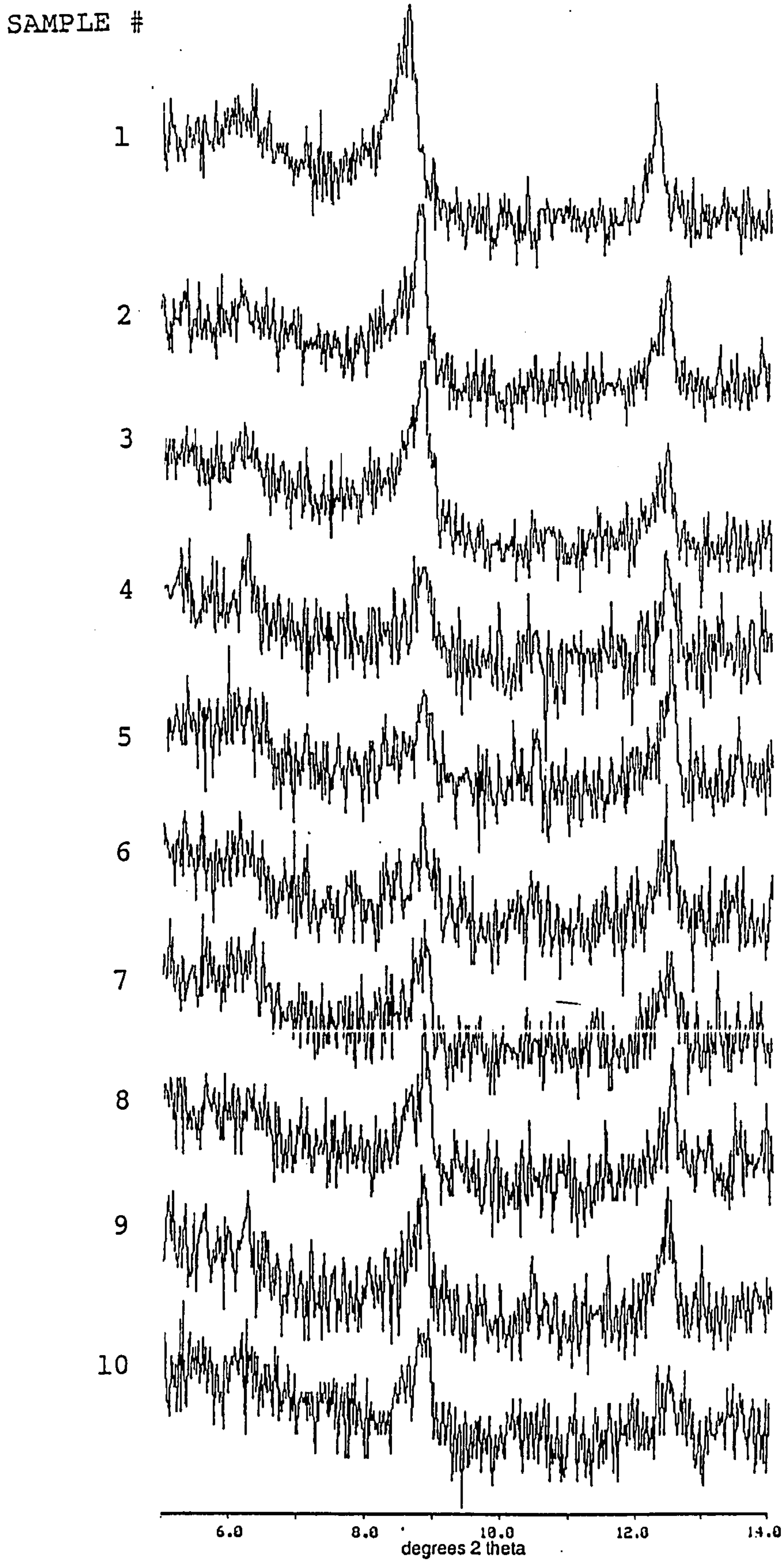

Figure 50. X-ray diffractograms.

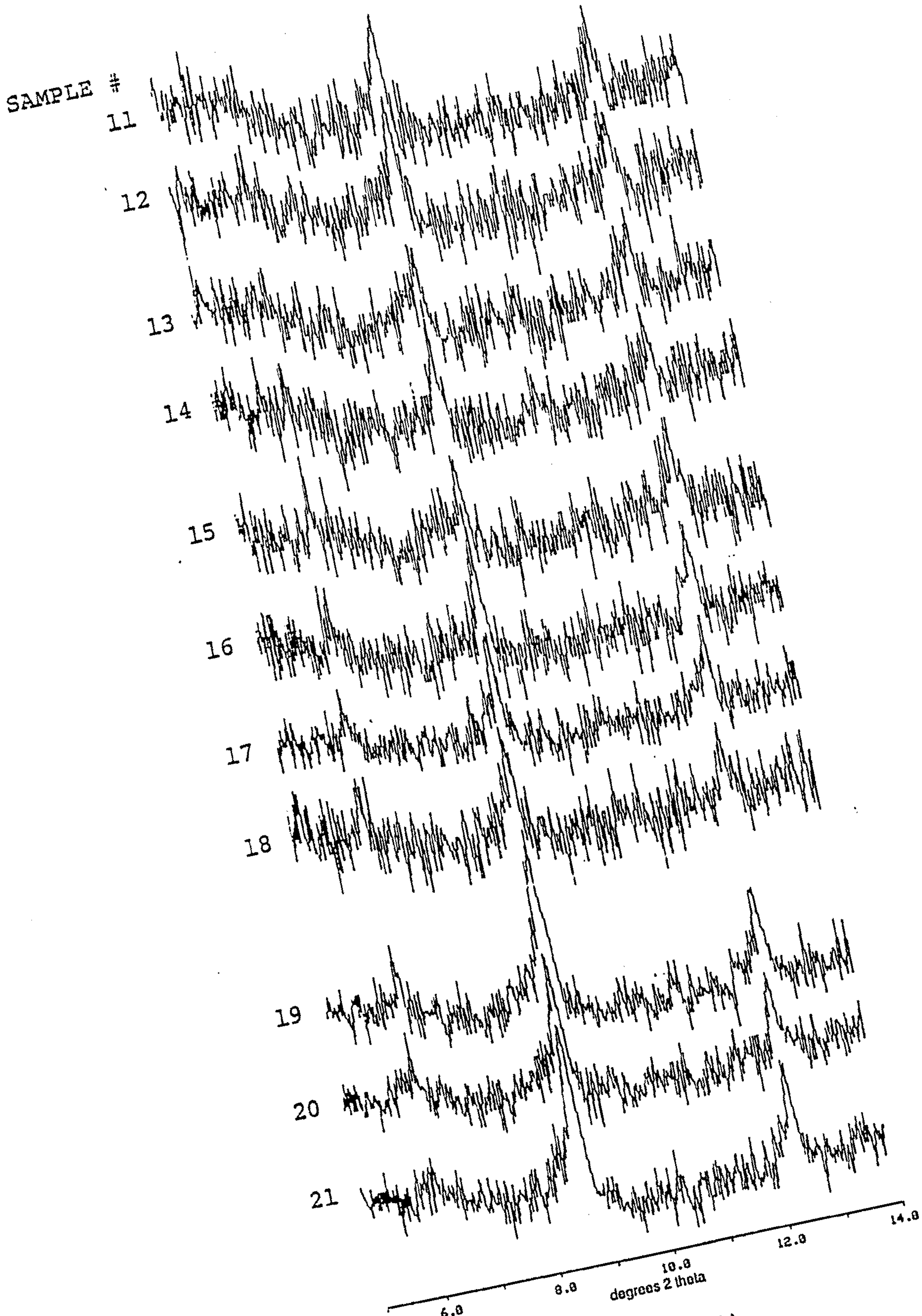

Figure 50. (cont'd.).

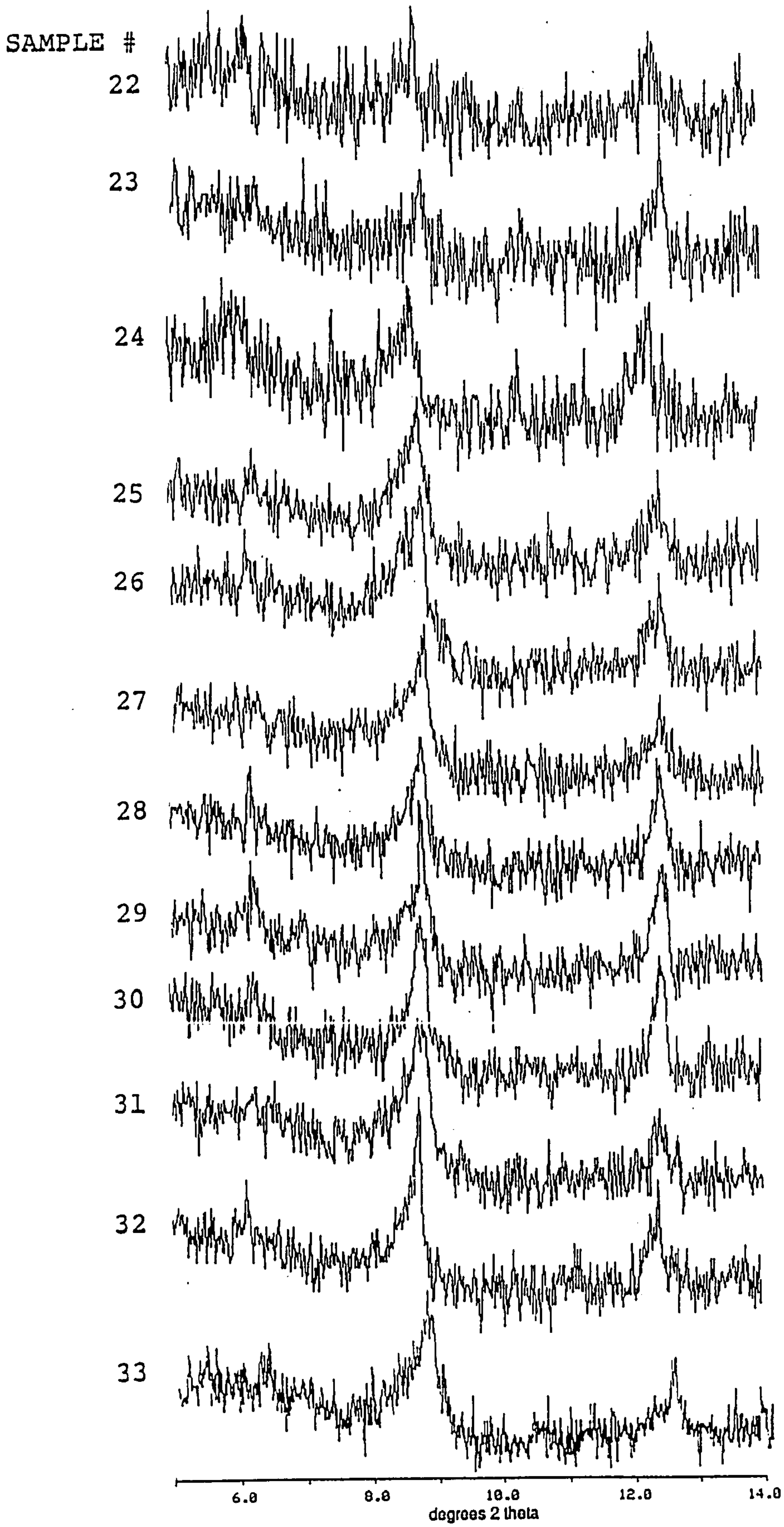

Figure 50. (cont'd.).

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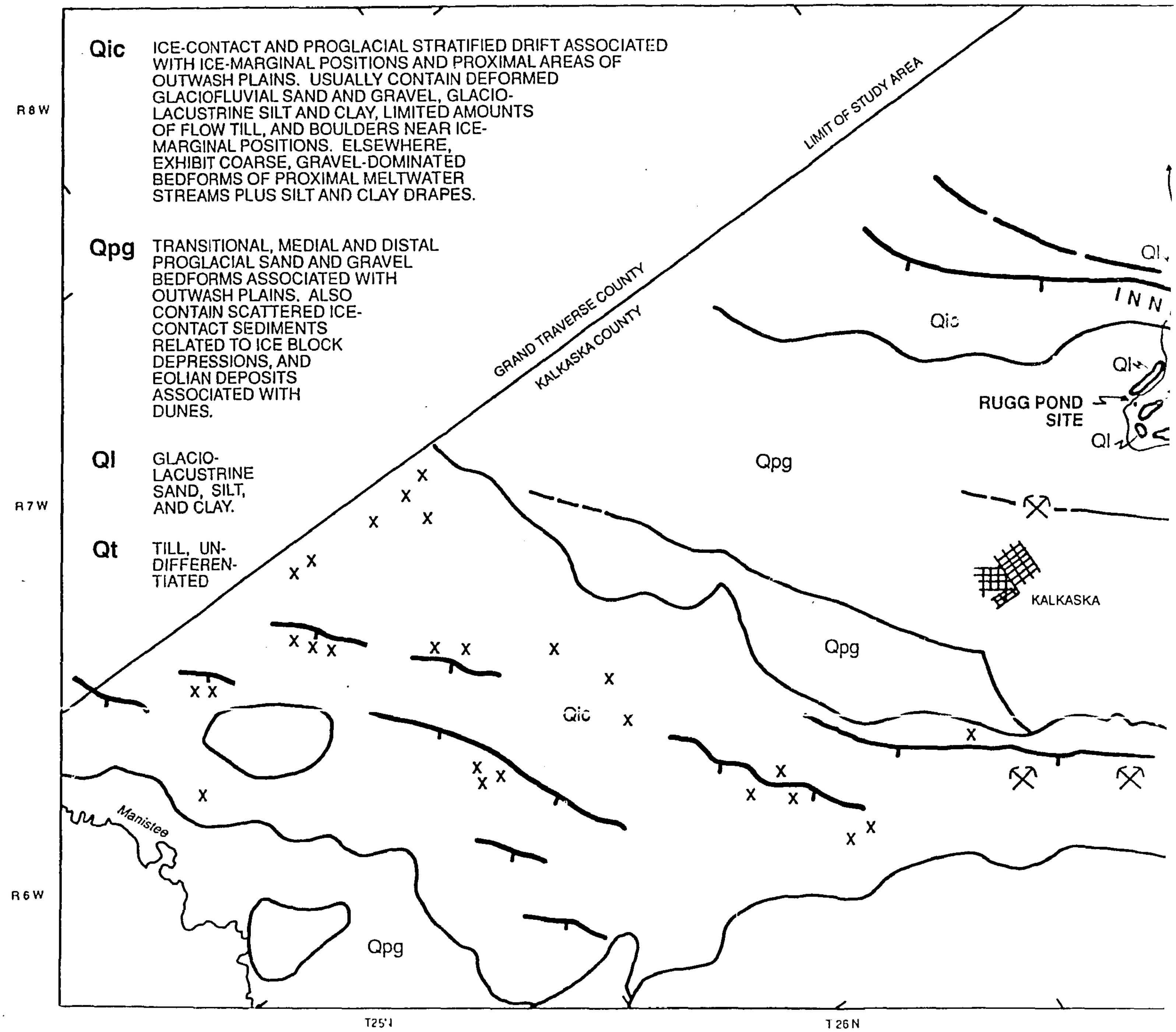
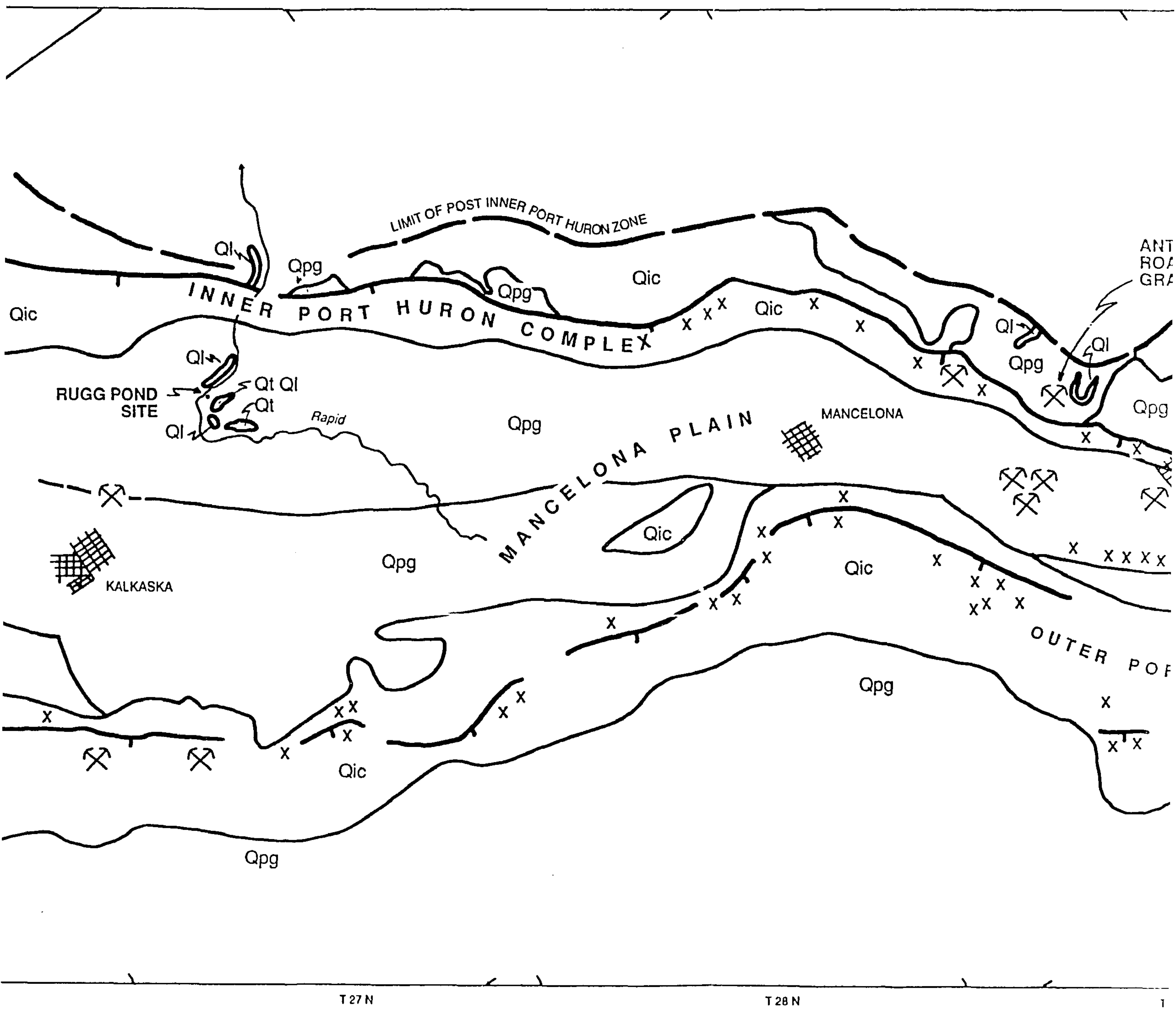
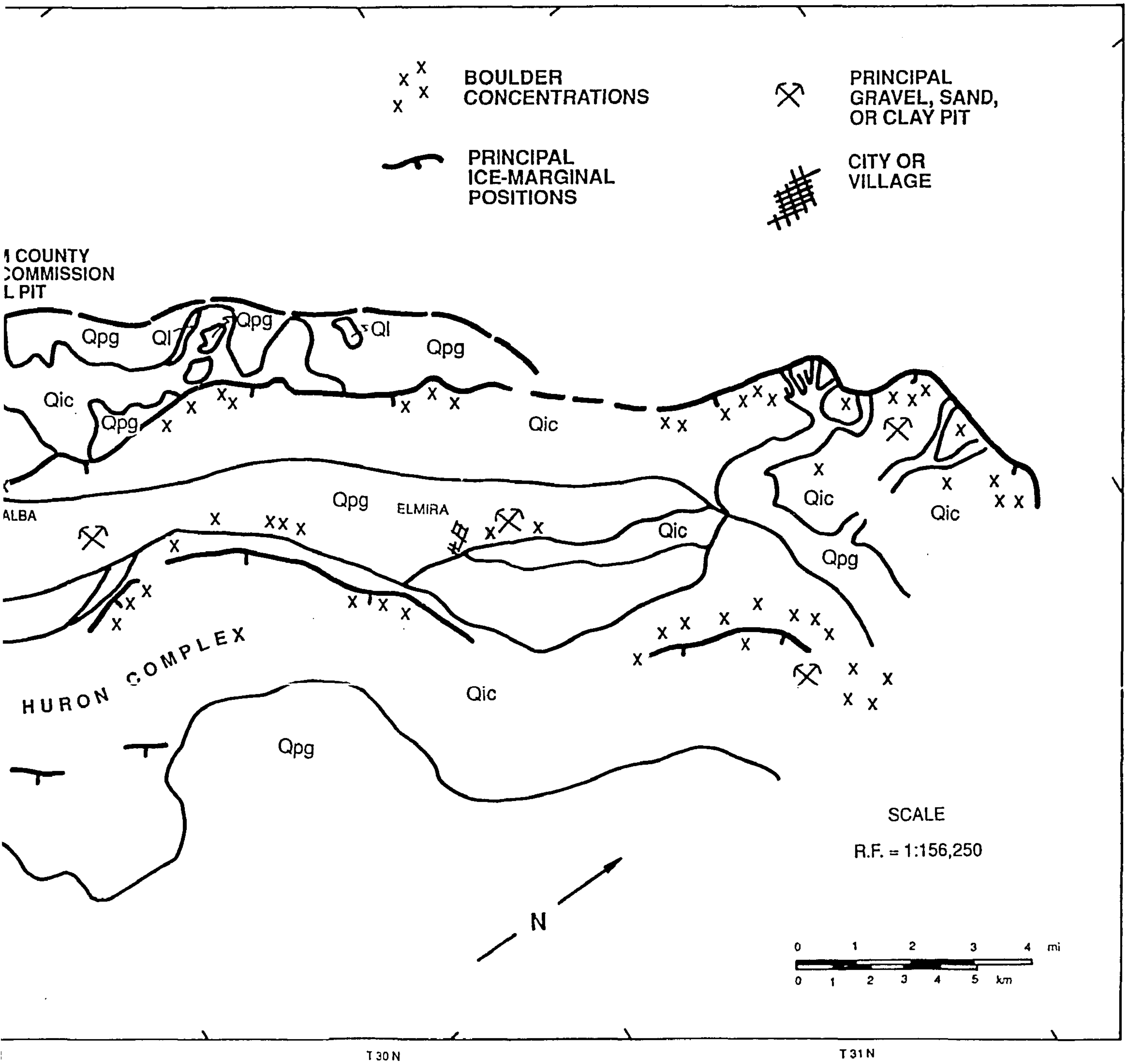

Qic
ICE-CONTACT AND PROGLACIAL STRATIFIED DRIFT ASSOCIATED WITH ICE-MARGINAL POSITIONS AND PROXIMAL AREAS OF OUTWASH PLAINS. USUALLY CONTAIN DEFORMED GLACIOFLUVIAL SAND AND GRAVEL, GLACIO-LACUSTRINE SILT AND CLAY, LIMITED AMOUNTS OF FLOW TILL, AND BOULDERS NEAR ICE-MARGINAL POSITIONS. ELSEWHERE, EXHIBIT COARSE, GRAVEL-DOMINATED BEDFORMS OF PROXIMAL MELTWATER STREAMS PLUS SILT AND CLAY DRAPES.
Qpg
TRANSITIONAL, MEDIAL AND DISTAL PROGLACIAL SAND AND GRAVEL BEDFORMS ASSOCIATED WITH OUTWASH PLAINS. ALSO CONTAIN SCATTERED ICE-CONTACT SEDIMENTS RELATED TO ICE BLOCK DEPRESSIONS, AND EOLIAN DEPOSITS ASSOCIATED WITH DUNES.
Ql
GLACIO-LACUSTRINE SAND, SILT, AND CLAY.
Qt
TILL, UN-DIFFEREN-TIATED
LIMIT OF STUDY AREA
GRAND TRAVERSE COUNTY
KALKASKA COUNTY
R 8 W
R 7 W
R 6 W
T 25 N
T 26 N
Qic
Qpg
Ql
RUGG POND SITE
KALKASKA
Manistee

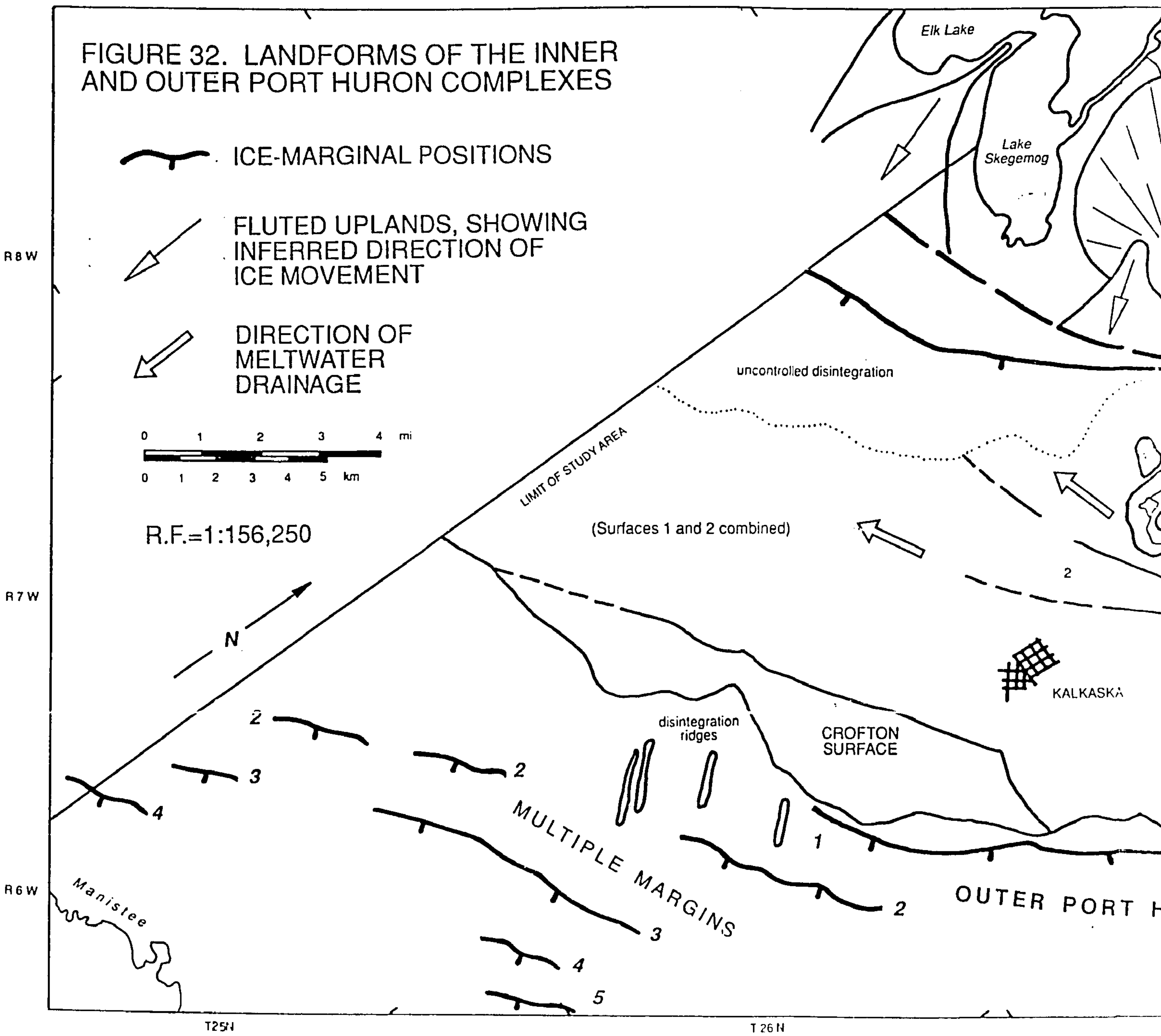
Figure 15.
Map of the surficial sediments of
the Inner and Outer Port Huron Complexes, northwestern southern Michigan.

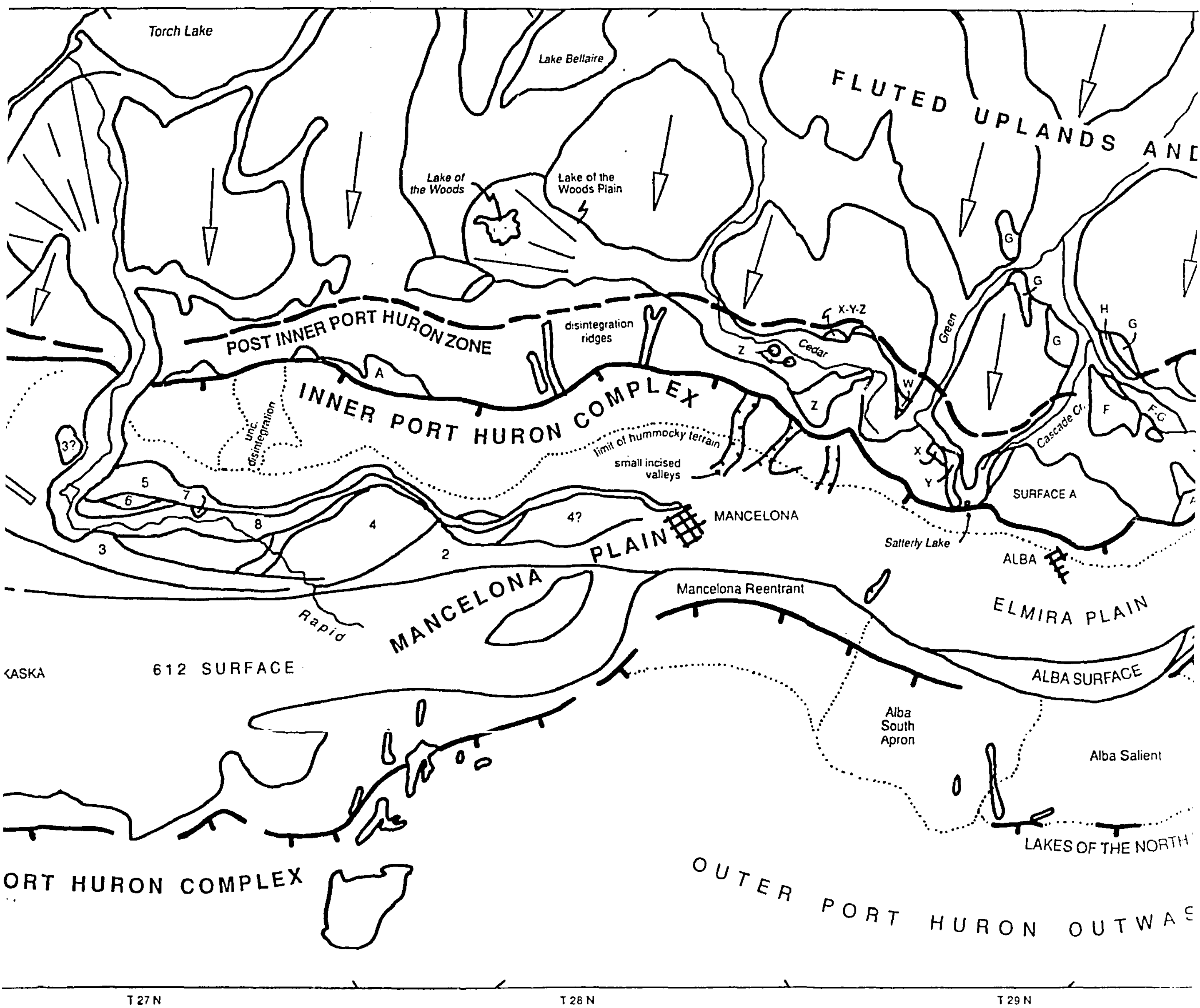


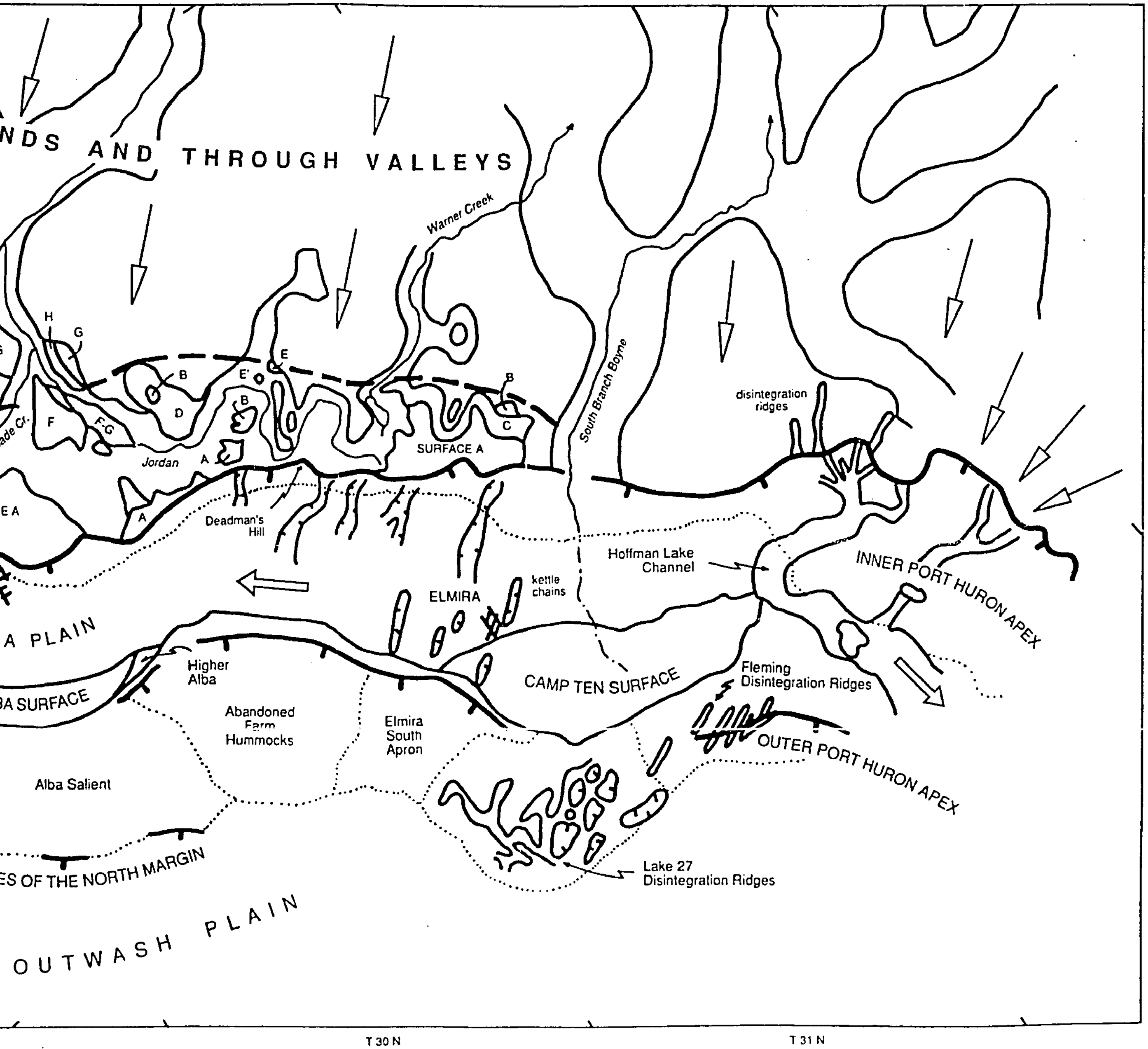


BOULDER CONCENTRATIONS
PRINCIPAL GRAVEL, SAND, OR CLAY PIT
PRINCIPAL ICE-MARGINAL POSITIONS
CITY OR VILLAGE
COUNTY
COMMISSION
L PIT
Qpg
Ql
Qic
ALBA
ELMIRA
HURON COMPLEX
SCALE
R.F. = 1:156,250
N
0 1 2 3 4 mi
0 1 2 3 4 5 km
T 30 N
T 31 N

FIGURE 32. LANDFORMS OF THE INNER AND OUTER PORT HURON COMPLEXES




Torch Lake
Lake Bellaire
FLUTED UPLANDS AND
Lake of the Woods
Lake of the Woods Plain
POST INNER PORT HURON ZONE
disintegration ridges
X-Y-Z
Cedar
Green
INNER PORT HURON COMPLEX
unc. disintegration
limit of hummocky terrain
small incised valleys
Cascade Cr.
SURFACE A
MANCELONA
Satterly Lake
ALBA
MANCELONA PLAIN
Mancelona Reentrant
ELMIRA PLAIN
Rapid
KASKA
612 SURFACE
ALBA SURFACE
Alba South Apron
Alba Salient
LAKES OF THE NORTH
ORT HURON COMPLEX
OUTER PORT HURON OUTWAS
T 27 N
T 28 N
T 29 N


NDS AND THROUGH VALLEYS
Warner Creek
South Branch Boyne
disintegration ridges
H
G
B
E
E'
D
F
F-G
C
SURFACE A
Jordan
A
EA
Deadman's Hill
Hoffman Lake Channel
INNER PORT HURON APEX
kettle chains
ELMIRA
A PLAIN
Higher Alba
BA SURFACE
CAMP TEN SURFACE
Fleming Disintegration Ridges
Abandoned Farm Hummocks
Elmira South Apron
OUTER PORT HURON APEX
Alba Salient
ES OF THE NORTH MARGIN
Lake 27 Disintegration Ridges
OUTWASH PLAIN
T 30 N
T 31 N