

*Characteristics of Fine-Grained Soils  
and  
Glacial Deposits in Northeastern Indiana  
for  
On-Site Wastewater Disposal Systems*



**INDIANA UNIVERSITY  
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*Department of Continuing Education*

*August 5 & 6, 1996*

*Monday, 1:00 - 5:00 p.m.  
(classroom)*

*Tuesday 8:00 a.m. - 5:00 p.m.  
(field trip)*



Field Notes <sup>Final</sup>  
Characteristics of Fine-Grained Soils and Glacial  
Deposits in Northeastern Indiana for On-site Wastewater  
Disposal Systems  
IPFW, Dept. of Geol. Ed. 1996  
Regional Geologic Setting  
GLACIAL GEOLOGY  
By Tony Fleming  
P. Fleming (1)

Most of northeast Indiana is dominated by thick glacial and post-glacial sediments that record numerous episodes of ice advance since the onset of the Ice Age. The majority of the glacial deposits in the region represent the most recent period of glacial activity, known as the late *Wisconsin Age*, which in Indiana took place between about 22,000 and 13,000 years ago. Consequently, this was one of the last parts of Indiana to become ice-free and the landscape is comparatively fresh. Stated slightly differently, the landscape of the basin has been little-altered since it was formed, thus the configurations of individual landforms tend to directly reflect the general shapes and styles of sediment bodies deposited by these latest glaciers and their meltwaters. An understanding of this relationship can be of considerable practical value, because variations in the landscape from place to place commonly provide a direct indication of parallel changes in the structure and other important physical properties of the underlying deposits and the soils developed on them.

The relationship between landforms and underlying depositional sequences is represented by the idea of *glacial terrains*. A glacial terrain is a geographically-defined feature characterized by a particular type of landform or group of related landforms, and a closely associated sequence of sediments that constitute those forms. Based on this definition, both the landforms and the underlying sediments in a terrain are indicative of a particular type of depositional environment, and are thus expected to possess a characteristic range of physical properties that strongly influence surface water hydrology, the movement of ground water, soil development, and a host of other environmental attributes. Definition and analysis of glacial terrains thus provide a basis for understanding the geologic history of the region as well as the distribution and character of a variety of important geotechnical and hydrogeologic parameters.

Over the course of the Ice Age (commonly called the *Pleistocene Epoch* by geologists), the continental ice sheets in the upper Midwest became increasingly differentiated into *glacial lobes* whose axes and regional flow directions corresponded closely in time and space to the carving of the Great Lakes and their major bays. During the late Wisconsin Age, northeastern Indiana was repeatedly covered by ice from two such lobes--the Saginaw Lobe from the north, and the Huron-Erie Lobe from the east. The shapes and regional distributions of landforms associated with the latter lobe suggest that it became progressively more dominated by ice flow from the Erie Lowland over the course of the late Wisconsin glaciation. It is thus characteristic to refer to the provenance of latest eastern source deposits as "Erie Lobe", whereas the earlier eastern source deposits in Indiana are commonly referred to as "Huron-Erie Lobe".

Northeastern Indiana can be thought of as comprising geologically distinct and physiographically contrasting northern and southern parts that flank a small central "core" located in the lowlands of eastern and central Allen County (figure 1). The glacial terrains in the southern half of the region were mainly produced during the most recent advances of the Erie Lobe, and are characterized by a relatively narrow range of depositional sequences and regionally extensive but relatively simple landforms. In contrast, the northern half of the region constitutes a much more complex, composite region formed by several overlapping advances of the Huron-Erie, Saginaw, and Erie Lobes (see box on **Summary of Late Wisconsin Glacial Events**). In general, the landforms and sedimentary sequences found in this interlobate part of northeastern Indiana are unsurpassed in their variety and complexity. The northern and southern parts of the region surround the western apex of the Maumee Lacustrine Plain, a low-lying, virtually featureless lake bottom that lay along the axis of ice flow from the Erie Basin and whose present form developed at the close of glaciation, when Glacial Lake Maumee covered most of northwestern Ohio and eastern Allen County.

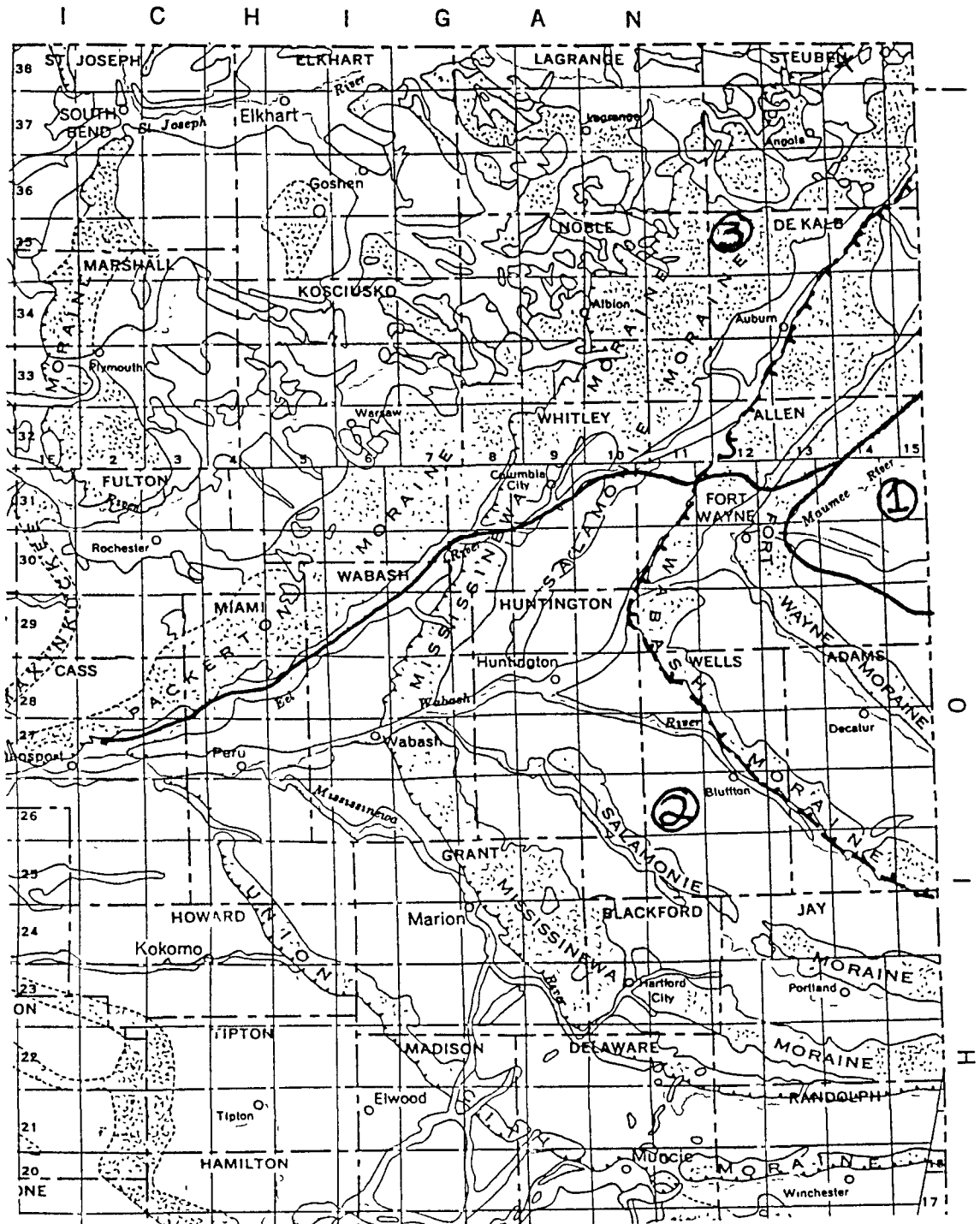


Figure 1. Map of northeastern Indiana showing the major physiographic divisions of the region, and major landforms and regional till textures associated with the Eric Lobe. The major physiographic divisions are bounded by heavy solid lines and identified by numbers: 1) the Maumee Lacustrine Plain, which constitutes the "core" of the Eric Lobe terrains; 2) the southern region of till plains and ridged end moraines, which is analogous to the "Tipton Till Plain" of Malott (1922); and 3) the northern "interlobate" region, which essentially corresponds to Malott's (1922) "Steuben Morainial Lake Area". The extent of latest Wisconsin clay-rich Eric Lobe deposits is rather sharply defined by the Union City Moraine in the south, but is less distinct in the north, lying somewhere within the Packerton and Mississinewa Moraines, where sediment textures and sequences are much more varied. Surficial Eric Lobe deposits are dominantly silty clay to silty-clay loam in texture within and east of the Wabash Moraine, but are mainly clay loam or coarser outboard. This regional textural boundary is indicated by the heavy hachured line that follows the front of the moraine.

## SUMMARY OF LATE WISCONSIN GLACIAL EVENTS IN THE MAUMEE RIVER BASIN, NORTHEASTERN INDIANA

Northeastern Indiana was repeatedly invaded by ice sheets from both the north and east during the past 1 to 2 million years. Most of the glacial sequences in the Maumee River Basin, as well as virtually all of the modern landforms, result from the latest events of the Wisconsin Age (see figure 4), and are generally between about 22,000 and 13,000 years old

The earliest known Wisconsin glaciers entered the basin about 22,000 ybp (years before present) from the east-northeast (Huron-Erie Lobe) and possibly also from the north-northwest (Saginaw Lobe) and probably covered the entire basin several times. Representative deposits from these advances are restricted to the subsurface within the Maumee River Basin. Subsurface relations in northwestern Allen County indicate pinkish clay-loam till of the Saginaw Lobe that may or may not be of Wisconsin age, underlying at least two sheets of grey loam till of the Huron-Erie Lobe. Saginaw Lobe till has not been observed in the southern or far eastern parts of the basin, where these earliest Wisconsin events are marked only by eastern source till. These sequences appear to be draped over a preexisting upland composed of pre-Wisconsin tills and outwash in the northern part of the basin, but the Huron-Erie Lobe tills and associated outwash were deposited directly on the bedrock in most of the southern part of the basin.

The buried surface of the Huron-Erie Lobe sequence exhibits considerable relief in some places, particularly in west-central Allen County, where it appears to comprise a buried morainal landscape composed of a series of till ridges and associated meltwater channels. These uplands effectively blocked meltwater drainage from the central part of the basin and led to the development of a series of regionally extensive glacial lakes that developed episodically in the lowlands to the east. These meltwater-fed lakes represent phases of ancestral Lake Erie and they profoundly influenced later glacial events in the central core of the basin and beyond.

Latest Wisconsin glaciers entered the Maumee Basin from the north and east at several times between about 17,000 and 15,000 ybp. The deposits of these advances include brown, sandy, coal- and sandstone-bearing till and outwash of the Saginaw Lobe, and light grey, silty to clayey tills of the Erie Lobe that contain sparse fragments of black shale and gypsiferous limestone as well as deformed rafts of lake mud. Regional terrain relations suggest that the two lobes were acting independently and that major periods of ice-margin advance of one lobe were not generally synchronous with those of the other. In general, a tongue of the Saginaw Lobe appears to have preoccupied the northern part of the basin as far south as northern Allen County. Collapse of this ice tongue produced extensive areas of irregular ablation topography and large blocks of stagnant ice that subsequently inhibited the northward progress of the Erie Lobe, contributing to the compressed and asymmetrical character of Erie Lobe moraines in that area. The pattern of glacial dynamics and resulting terrain configuration in the interlobate northern part of the basin are thus fundamentally different from those to the south, which resulted from extensive advances of the Erie Lobe over relatively smooth terrain.

Sandy till of the Saginaw Lobe is typically present in the subsurface in widely scattered localities throughout the northern basin. It is well-represented in northern Allen and southern Dekalb Counties, where it commonly overlies a persistent zone of basal outwash and is locally capped by a variety of ablation and ice-contact stratified deposits. This sequence generally becomes increasingly finer-grained to the southeast and grades into fan-deltas and other glacio-lacustrine sediments associated with the margin of ancestral Lake Erie in north-central Allen County. The latter stage of the glacial activity that produced this sequence appears to have been characterized by general zonal stagnation and irregular ice margin retreat, in which large blocks of stagnant ice became buried in their own debris, including several ice-contact outwash fans. Deposition was focussed at or near the southern margin of the glacier in Allen and southern Dekalb Counties where the sequence attains its greatest thickness and continuity, whereas these deposits become much less prominent and more internally variable northward in Dekalb County.

Sandy till-like sediments of similar aspect also occur in northern Steuben County, but they appear to belong to a younger, outwash-dominated depositional sequence. This sequence probably forms the buried eastern edge of a line of massive outwash fans (the Angola, Sturgis, and Brighton fans) and associated fan-marginal channels (Pigeon and Fawn River troughs) that are exposed at the surface beyond the Erie Lobe overlap just west of the basin divide. These deposits appear to be inset into

a "hole" or depositional basin left by the collapse of earlier Saginaw Lobe ice, they may represent a distinctly younger ice advance or they could be the result of reactivation of the formerly stagnating central ice mass. Their relationship in time to Erie Lobe events is problematic because the three outer Erie Lobe moraines so evident to the south are completely attenuated into one broad upland in Steuben County. The best available evidence suggests that they may be approximately contemporaneous with deposition of the Mississippian Moraine.

The grey, fine-grained tills of the Erie Lobe comprise the principal surficial sediment throughout the basin. Incorporation of lacustrine mud as the ice advanced through the bed of ancestral Lake Erie overwhelmed the coarser parts of the sediment load and led to deposition of tills that are commonly about 90% silt and clay and only rarely contain appreciable sand lenses. The earliest Erie Lobe advance(s) extended as far as 50 miles south of the central basin and left a relatively uniform sheet of clay-loam till in their wake. In contrast, ice flowing northward out of the lake plain was impeded by the irregular Saginaw Lobe ablation drift and dead ice and probably took much longer to reach less distant terminal positions. The landscape associated with the Erie Lobe till in this part of the basin locally exhibits structural patterns that more closely resemble the likely orientations of crevasses and ice marginal features of the underlying Saginaw Lobe. This strongly palimpsest topography resulted from the melting of buried Saginaw Lobe ice masses and subsequent collapse of overlying materials. Not surprisingly, the earliest Erie Lobe deposits in the northern basin are more variable in their texture and structure than elsewhere and are locally associated with small ice-contact sand and gravel bodies.

Erie Lobe tills present within the Wabash Moraine and points inward (eastward) are predominantly thick silty-clay to silty-clay loams, and contain remarkably few large clasts. The finer texture could have resulted from a change in the sediment source during the same advance that produced the earlier tills, but the abrupt contrast across the outer edge of the Wabash argues against this possibility. A more likely possibility is that the ice front retreated eastward sufficiently far to allow another lake phase to develop in the lake basin and accumulate lake clays. These clays were subsequently incorporated into the ice as it readvanced to the Wabash Moraine. The moraine is generally a massive physiographic feature, especially in the northern basin, and the ice front probably remained at this position for a substantial period. Meltwater draining the northern part of the ice sheet cut tunnel valleys such as Cedar Creek Canyon, which in turn fed the ice-marginal Eel River. Outwash bodies also become increasingly prevalent within the moraine northward from Allen County, culminating in the large Fish Creek fan that forms the morainal front in eastern Steuben County. The northernmost part of the moraine thus may partly be a complex of overridden outwash fans.

The formation and subsequent catastrophic drainage of glacial Lake Maumee represent the final events in the development of the Maumee Basin during the late Wisconsin Age. Fine-grained lake sediments and gravelly beach ridges can be traced far into Ohio, indicating that the lakebed covered several thousand square miles and may have had a maximum water depth approaching 75 feet in some places. Perhaps in response to ice-margin fluctuations further east in the Erie Basin, the level of glacial Lake Maumee appears to have overtopped a sag in the Fort Wayne Moraine near what is now downtown Fort Wayne, unleashing a massive volume of water often referred to as the Maumee Torrent. This catastrophic event scoured out a 1- to 2-mile wide outlet known as the Wabash-Erie Channel that is one of the most striking topographic features in the basin. Following the drainage of glacial Lake Maumee, regional surface drainage continued to flow southwest through the Wabash-Erie Channel for hundreds, or perhaps thousands, of years until the Erie Basin became ice-free and an eastward drainage route was opened. The record of this early stage of post-glacial drainage is well preserved in the bottom of the Wabash-Erie Channel near Fort Wayne. There, as much as 30 feet of fine sand, silt, and organic sediments were deposited in a complex fluvial-lacustrine-palustrine environment during the interval following the cutting of the outlet and leading up to the complete capture of surface drainage by the Maumee River. The course of the Maumee River generally follows the route of an earlier subglacial channel, but the modern, eastbound drainage system did not become established until headward erosion by the river captured the St. Joseph and St. Marys Rivers.

Adapted from "Glacial Geology" by A. H. ... in ...  
Resources Availability in the Maumee River Basin ...  
Division of Water ...

**ERIE LOBE**

General ice margin retreat. Deposition of *Fort Wayne Moraine* during stillstand. Ice retreats back into Ohio

Readvance of ice front to *Wabash Moraine* (silty-clay and silty clay-loam inner tills of the *Lagro Fm*) (event 6)

General retreat of ice front eastward into Lake Erie Basin. Formation of *Musstown Moraine* during minor readvance (clay-loam outer tills of the *Lagro Formation*) (event 5)

Ice overrides lake basin and spreads both north and south from core of basin, ultimately reaching terminal position south of basin at *Union City Moraine* while abutting and eventually overriding large dead-ice landforms and stagnant ice masses of the *Saginaw Lobe* to north (clay-loam to silt loam outer tills of *Lagro Formation*) (event 3)

Erie sublobe begins advancing through western Ohio, incorporating abundant lake mud into base of ice

Ice front retreats far back into eastern Great Lakes (*Erie Interstadial*)

Main advances of *Huron-Erie Lobe* into central Indiana. Formation of complex of buried recessional moraines in western and central Allen County (*grey loam tills of the Trafalgar Formation*) (event 1b)

**ANCESTRAL LAKE ERIE**

Minor readvance of ice further east in Lake Erie causes lake level to overtop sag in *Fort Wayne Moraine*, resulting in catastrophic drainage via *Wabash-Erie Channel*

Opening of lake basin in front of receding ice and development of *Glacial Lake Maumee*. Deposition of lake mud in central basin and beach deposits along shorelines

Closing of lake basin, incorporation of lake clays into overriding ice

Proglacial lake develops in Erie Basin. Accumulation of lake clays derived from recently deglaciated landscape to north and south

Catastrophic(?) drainage of lake to southwest

Area of lake basin becomes attenuated while meltwater input increases from both ice lobes

Large proglacial lake impounded between moraine complex to west and ice front to east. (deltaic silt, sand, and waterlain till from retreating *Huron-Erie Lobe*, sand and silt in fan-deltas from *Saginaw Lobe* meltwater streams)

**SAGINAW LOBE**

Melting of buried ice masses in northern basin creates classic *knob-and-kettle topography* and numerous lakes and wetlands

Zonal stagnation and general retreat

Ice front readvances into northern Steuben and Lagrange Counties. Deposition of outwash fans (*Brighton, Sturgis, Angola fans*) and ice-marginal channels (*Fawn and Pigeon River troughs*) mainly just west of *Maumee Basin* (event 4)

General collapse and zonal stagnation (*ice-contact fans; hummocky ablation complex; dead-ice landforms*)

Southern edge of lobe advances to terminal position in northern Allen County (*proglacial outwash, sandy loam till, fan-deltas*) (event 2)

General recession or zonal stagnation

Ice advances across preexisting upland in Noble and Dekalb Counties reaching at least to northwestern Allen County (*pinkish clay loam till*) (event 1a) (may be pre-Wisconsin age)

**LATE WISCONSIN SEQUENCES**

**Erie Lobe Sequences (Lagro Formation)**

Silty-clay (-loam) inner till; outwash (stippled)

Clay-loam outer till, ice-contact sand and gravel

**Huron-Erie Lobe Sequences (Trafalgar Formation)**

Loam till, sand and gravel

**Glaciolacustrine Sequences (ancestral Lake Erie)**

Sand, silt, and clay in delta, beach zones, and distal rhythmites

Sand, silt, and clay in delta, beach zones, and distal rhythmites

**Saginaw Lobe Sequences**

Outwash fans, sandy loam till

Sandy loam till, outwash, ablation deposits and dead-ice landforms

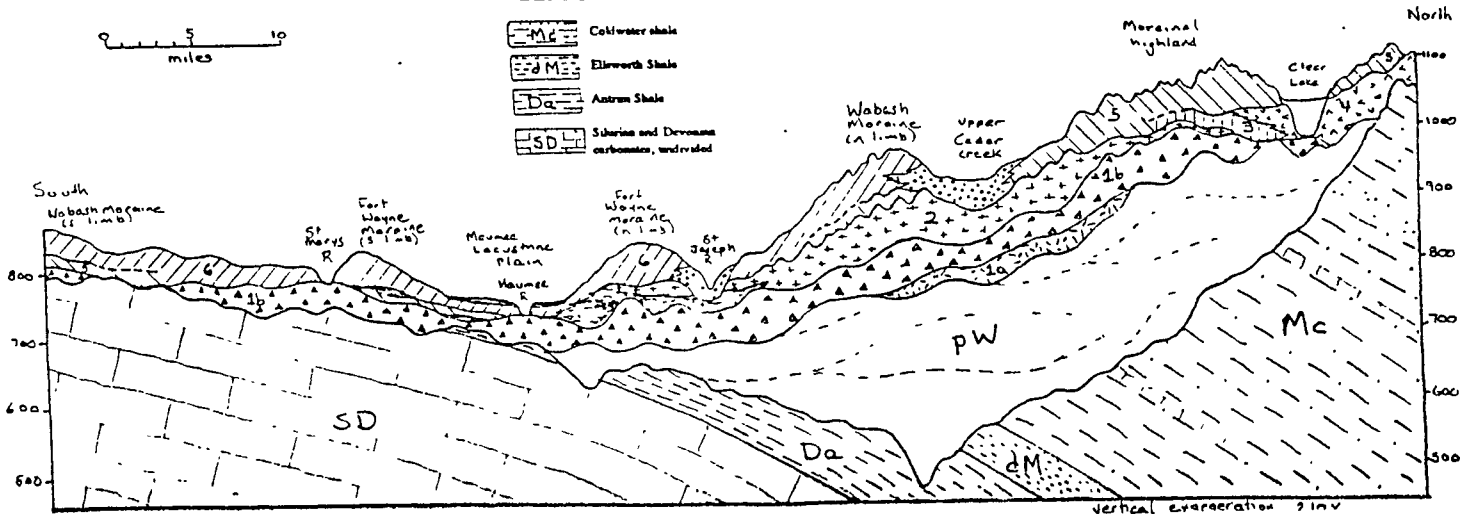
Clay loam till

**PRE-WISCONSIN SEQUENCES (UNDIFFERENTIATED)**

Loamy and clayey till, sand and gravel

**BEDROCK UNITS**

- Mc** Colwater shale
- dM** Ellsworth Shale
- Da** Antrim Shale
- SD** Silurian and Devonian carbonates, undivided



In this course we are chiefly concerned with the uppermost sequence of glacial deposits upon which most of the modern soils and landscape are developed. These distinctive, predominantly clay-rich deposits are the result of latest Erie Lobe activity circa 14,000 to 15,000 ybp (years before present), and are referred to by geologists as the Lagro Formation (Wayne, 1963), a name derived from exposures near the village of Lagro in Wabash County. The Lagro Formation covers a large area of northeastern Indiana (Gray, 1989), hence its sedimentary and hydrogeologic properties are of considerable interest for a variety of reasons, such as ground-water recharge and protection, solid waste disposal, wetlands, and soil science, among others.

### Overview of Sedimentary Processes and Environments

Most deposition associated with glaciers takes place at or near the ice margin. The particular type of sedimentary sequence, and the landforms associated with it, depend on the dynamics of the glacier, the mechanics of sediment transport within the glacier, the source of the sediment, and the style of deposition that results. In general, materials deposited by a robust, active ice sheet tend to be more uniform in both thickness and sediment type than those deposited from stagnant or sluggish ice. Both styles of deposition appear to have operated at different times during the glacial history of the region.

A popular misconception involves the idea of glacier "retreat". When a glacier recedes, it does not move backwards; instead, the ice margin melts back while, in many cases, the body of the ice sheet is still moving forward. This concept is extremely important, because sediment is still being transported to the ice margin, even though the glacier may be in an overall recessional mode. Most sediment deposition occurs during this stage of glaciation, at least that which is preserved in the modern landscape. In contrast, sediment deposited when the ice margin is advancing is less likely to be preserved because of the possibility of severe erosion beneath the inner part of an ice sheet.

Over a long period of time, accumulation of ice toward the center of a glacier is balanced by melting at and near the margin. This equilibrium has two important consequences. First, the outward flow of ice within the glacier transports sediment to the ice margin, where it is deposited by a variety of processes. Second, meltwater emanates from the melting ice front, where it forms streams that flow both away from and parallel to the ice margin. The high energy typical of most meltwater streams results in the removal of silt and clay from the glacial debris. This process concentrates sand and gravel, which is commonly deposited in the form of *outwash*. The relative coarseness of the outwash in any given depositional system tends to diminish with increasing distance from the ice front. Outwash bodies in northeastern Indiana range from narrow, discontinuous channels to broad, regionally extensive plains and fans. The detailed geometry of outwash bodies depends on such factors as the configuration of the landscape over which the meltwater flows, the size and location of meltwater outlets from the ice front, the sediment load each meltwater stream carries, and the behavior and duration of the ice front at a particular location. Some examples of regional landforms composed of outwash in northeast Indiana include the small *valley trains*, or *sluiceways* along the St. Joseph and Wabash Rivers, as well as the massive *aprons* and *fans* in the vicinity of Shipshewana (northwestern LaGrange County), Fish Creek (eastern Steuben County), and Topeka (southern LaGrange County).

Sand and gravel also occurs in ridged or hummocky form at some places, and is generally referred to as *ice-contact stratified drift*. Such deposits are not true outwash because they are typically deposited in, on, or against glacial ice, rather than out in front of the ice margin. Subsequent melting of the supporting ice caused these sediments to collapse, giving them their characteristically irregular form. Common types of ice-contact stratified deposits include narrow, linear, and commonly sharp-peaked ridges of sand and gravel referred to as *eskers*; and irregular complexes of sand, gravel, and till-like sediment known as *kames*, that range in shape from semi-conical mounds to broad-crested, hummocky ridges.

*Debris flows* are a significant component of many glacial deposits. Although a variety of processes can be involved in the formation of these mass movement deposits, most debris flows of glacial origin form when the loss of supporting ice induces the slumping and sliding of recently thawed supersaturated sediments. Many debris flow deposits closely resemble glacial till and are sometimes referred to as *flow tills* and *mud flows*. Because of their similarity, the distinction between debris flows and true glacial till can be problematic in Pleistocene deposits. This is especially true where the two occur together in the subsurface within the same depositional sequence. It is best in such instances, therefore, to refer to the entire assemblage as *till-like sediment* or *diamicton* (an increasingly popular term for massive, poorly sorted, and poorly stratified sediment), which acknowledges the variety of processes and sediment types represented. Debris flows can be formed from almost any kind of pre-existing sediment and are found in widely scattered places throughout northeastern Indiana. However, flowage of glacial sediments was most commonly triggered by the melting of adjacent or subjacent ice blocks, hence debris flows are most abundant in the northern half of the region, and in hummocky end moraines elsewhere.

Ice-contact stratified deposits, debris flows, small bodies of outwash in channelized form, and localized pond sediments commonly occur together as *ablation complexes* formed during the melting of an ice sheet. Ablation complexes can be quite thick and widespread when large parts of an ice lobe become stagnant and melt via the process of downwasting. This situation was evidently characteristic of many places in the northern part of the region, and resulted in large-scale ablation deposits within which individual sediment bodies commonly have little continuity and range widely in many of their physical properties. In contrast, ablation complexes appear to be much thinner and predominantly fine-grained in the lower-relief terrains to the south, with the exception of some segments of Erie Lobe end moraines, where they are locally thick.

The land surface over large parts of northeast Indiana is underlain by a variety of *till* and *till-like deposits*--mainly fine- to medium-grained, poorly-sorted, and poorly stratified sediments that were transported near the base of the glacier and deposited directly by ice. Each ice advance that affected northeastern Indiana tended to produce a characteristic till sheet that, on a regional scale, can be distinguished from other till sheets on the basis of grain-size distribution, combinations of rock and mineral fragments unique to a particular source area, clay mineralogy, and other diagnostic attributes. The relative proportions of sand, silt, and clay that form the matrix of any particular till unit depend on the *source area* of the glacier as well as on the kinds of processes that release the sediment from the ice. These processes, together with the prevailing conditions at the bed of the glacier during and after till deposition strongly influence the physical properties of a particular till unit. For example, the surface till over most of northeastern Indiana is typically clay-rich, reflecting the abundance of both lake mud and shale bedrock in the source area of the Erie Lobe east of the basin. In contrast, tills of the Saginaw Lobe, which underlie Erie Lobe tills in many places in the northern part of the basin, are commonly sandy due to the combination of coarse-grained bedrock and abundant outwash in the source area, and the removal of fine particles by meltwater during deposition from stagnant or sluggish ice. Somewhat older Huron-Erie Lobe tills (the Trafalgar Formation of Wayne, 1963) are present in the subsurface throughout the basin, are silty or loamy in texture, and are dominated by particles derived from a mixed bedrock and drift source.

Some till-like sediments were extensively reworked by meltwater and mass movement (debris flows), whereas others were not (Table 1). Some were deposited in lakes or meltwater channels, whereas others were deposited in a terrestrial setting. Most of these sediments contain scattered rock fragments set in an *overconsolidated* fine-grained matrix. Because of the superficial similarities, nearly all of these sediments have traditionally been referred to or mapped as "till", a practice that greatly oversimplifies the range of processes involved in their deposition and, more importantly, tends to obscure major differences in physical properties (e.g., the ability to transmit water) that result from seemingly minor differences in genesis. Because of the particular relevance to this course, the following section briefly summarizes the major categories of fine-grained glacial sediment historically called "till", their recognition, and the different



physical properties that typify each. Note that this discussion pertains to temperate ice sheets such as those that invaded Indiana.

### Till and Till-Like Glacial Sediments

In the strict sense of the word, *till* refers to massive, unsorted sediment that was deposited directly from ice with NO reworking by mass movement or meltwater. Most till is deposited at the base of the glacier close to the ice margin and is referred to as *basal till*. The texture and structure of basal till directly reflect processes associated with the latest movements of the ice. There are two main varieties of basal till:

1) *lodgement till*, deposited by plastering of individual particles onto the substrate beneath moving ice. Lodgement till typically exhibits a pronounced *fabric* produced by strong alignment of visible clasts and by shear planes. Both of these features tend to dip moderately up-ice; that is, in the direction from which the ice advanced. There is little or no stratification, although small folds of underlying or enclosed silt and sand lenses may be locally common. The till is typically hard, compact, fissile, and is commonly jointed. Jointing in fine-grained (i.e., clayey) lodgement till may be very well developed, and individual joints often occur in distinct sets whose preferred orientations show a geometric and structural relationship to ice flow direction (see box on **Geotechnical Properties of Erie Lobe Till Units**).

2) *meltout till*, deposited by passive meltout of debris from layers of debris-rich ice beneath a glacier. The ice above these debris-rich zones may or may not be moving. Meltout till is typically somewhat coarser than lodgement till from the same glacier due to the washing out of fines by interstitial meltwater. It also exhibits a strong fabric; although visible clasts are strongly aligned, they tend to lie in a sub-horizontal plane, which results from the passive melting of ice that surrounds and supports the clasts. Some stratification may be evident and is usually the result of alternating bands of ice having different debris concentrations. Small pods and seams of silt and sand as little as a few grains thick may be common, and represent former zones of clean ice where meltwater became concentrated during the meltout process. Layers are commonly draped over large clasts, signifying passive meltout. The till is typically hard, fissile, and compact, although somewhat less so than lodgement till. Jointing may or may not be present depending on whether the overlying glacier was in motion and imparting shear stress at the time of deposition, or the till was subsequently overridden by a younger ice advance.

*Supraglacial till* (“*ablation till*”). In some cases it can be shown that till was deposited on top of glacier ice and subsequently let down in-situ upon melting of the ice. Such till lacks strong fabric, is generally not compact, and is not jointed. This type of process is relatively unusual, however, because most sediment released atop the ice is supersaturated and experiences a loss of support due to uneven melting of the ice beneath. Consequently most so-called “supraglacial till” is really debris flows that have lost most or all of the original characteristics of the till.

*Debris flows* (also called *flow tills* or *mud flows*) are produced in many environments on and around glaciers. They appear to be most common in proglacial settings, that is, they are commonly found along the ice front, or margin. Melting of ice along the glacier margin releases large amounts of sediment, most of which is supersaturated with meltwater, recently thawed, and thus lacking appreciable shear strength. Any sediment deposited on, in, or against ice is likely to become remobilized once the supporting ice begins to melt. Consequently an apron of debris flows is very common along the toe of the glacier, and may build up to considerable thickness if the ice margin remains stationary for a long period, such as along an end moraine. Debris flows may be derived from almost any type of preexisting sediment, including till, lake sediment, and even sand and gravel. Most commonly they are derived from remobilization of freshly deposited till or from debris exposed on the surface of the glacier.

Debris flows are distinguished by several features. They are locally stratified, at scales ranging from less than a centimeter to several meters. They are commonly interbedded with lenses of sand and gravel, especially if the flows were deposited in front of the ice or in a meltwater channel where outwash was also being deposited. The edges of flows are usually marked by conspicuous "levees" composed of coarse fragments that dropped out of suspension. Fragments within the flow may or may not exhibit a preferred alignment, but where this fabric element does occur, the long axes of ellipsoidal clasts are typically transverse to the direction of flow--i.e., exactly opposite that observed in basal till. The base of debris flows frequently exhibit highly irregular contacts with underlying units (especially where they overlie sand and gravel) and may be injected by diapirs and dikes of sand. Small clusters, or "traffic jams" of pebbles and cobbles are common in the body of flows and mark former low-velocity zones. Debris flows generally do not exhibit pervasive jointing, although some joints oriented transverse to the flow direction may be present in cohesive units deposited on sloping substrates. Debris flows may be extremely hard if they were subjected to repeated wetting and drying cycles by meltwater in the proglacial environment, a process that can result in extreme overconsolidation.

Debris flows are commonly observed interbedded with glacial lake deposits, indicating that they were deposited in water. Such flows may be obviously interbedded with laminated silt and clay, and they often lack large clasts except in the most proximal (closest to the ice) portions. If deposition was extremely slow in quiet water, they may appear as absolutely massive bodies composed of silty clay. Most commonly, subaqueous debris flows moved downslope as turbidity currents and thus show stratification, both internally and with other debris flows.

Attribute	Basal Till		Terrestrial Debris Flows		Waterlain Diamicton
	Lodgement	Meltout	Proglacial	Supraglacial	
Where deposited	Under moving ice	Under passive ice	Ice margin	Ice surface	Lakes in front of ice margin
Sorting	Poor	Poor	Weak to poor	Weak to poor	Poor to fair
Stratification	Weak to none	Weak	Fair to weak	Weak to none	Fair to weak
Interbedded sediment	Usually none	Thin sand or silt stringers	Outwash	Highly variable	Laminated mud and sand
Surface form	Flat, ridged, or streamlined	Flat, ridged, or streamlined	Sloping or hummocky	Hummocky	Flat or gently sloping
Consistency	Hard	Stiff to hard	Stiff or hard	Loose	Stiff
Clast shape	Faceted	Faceted	Angular	Angular	Often lacks large clasts
Clast alignment	Strong, dips up-ice	Strong, horizontal	Weak, may be transverse	Random	Often lacks large clasts
Fabric elements	Strong, shear planes parallel clast alignment	Moderately strong, rare shear planes	Clast levees define edges and front of unit	Random	Usually none
Fracturing	Well developed, near-vertical	Varies widely, near-vertical	Weak, usually transverse, fissile	Not common	Weak, not common
Continuity	Well developed	Well developed	Usually poor	Poor	Poor to moderate
Other aspects	Commonly folded or thrust faulted	Layers draped over large clasts	Clast aggregates common	Commonly very coarse and stony	May show graded bedding

Table 1. Characteristics and diagnostic attributes of fine-grained till and till-like sediments.

## GEOTECHNICAL PROPERTIES OF ERIE LOBE TILL UNITS

The bulk properties of a body of rock or sediment that affect its engineering and hydrologic behavior are collectively referred to as geotechnical properties. Two properties of particular interest in the glacial tills of the Maumee Basin include consistency, which is essentially a measure of the unconfined compressive strength or consolidation of the till matrix, and the orientations of discontinuities, such as joints, that separate the matrix into discrete blocks. The development of these properties generally depends on the interaction of several main factors, such as grain size distribution, mineralogy; the type of sequence within which the till occurs; and the stress history of the till during and after deposition. Consistency and discontinuities commonly control the response of the till to a variety of near-surface engineering and hydrologic applications, hence a knowledge of their origin and characteristics is useful in the design of many types of projects.

In-situ bulk consistency is commonly measured in terms of blow counts, which refers to the number of blows required to drive a sampling device a specified distance through the till. This procedure is typically carried out as part of foundation test borings and other exploratory drilling and utilizes a sliding, 140-pound hammer mounted on the drill rod. Glacial tills are commonly found to be substantially harder to penetrate than would be expected from their present shallow depth of burial, and are referred to as overconsolidated. In particular, the sequence of loamy Huron-Erie Lobe tills of the Trafalgar Formation is severely overconsolidated, especially along its buried upper surface. More than 300 blows have been required to penetrate less than 12 inches into the till at some places—an extraordinarily hard consistency for "unconsolidated" sediment. Although the Trafalgar Formation is not the immediate surface till in the basin, its buried surface lies at relatively shallow depths (5-25 feet) in many low-lying places in the metropolitan Fort Wayne area, where it can pose a significant obstacle to excavations and test drilling, particularly where these operations are performed with small equipment. On the other hand, these same qualities typically result in superior bearing strength for supporting large loads such as tall buildings.

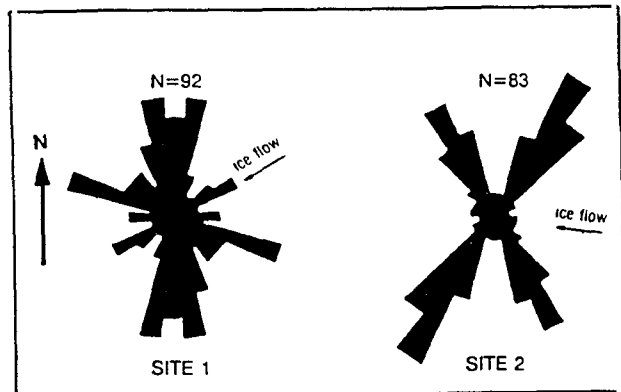
The origin of the extreme overconsolidation in these tills is not clear and probably results from the complex interaction of several factors. Overconsolidation in glacial sediments is commonly perceived to be mostly attributable to the great weight of the overriding glacier during till deposition, but this does not seem likely because the downward force at the sole of most glaciers is commonly offset by extremely high pore pressures attributable to build up of meltwater along the ice-sediment interface. Numerous exposures of the Trafalgar Formation in Allen County provide abundant evidence for formerly high pore pressures, most directly in the form of various dewatering structures, and indirectly by the presence of low-permeability units within and beneath the till that would likely have restricted the flow of meltwater away from the interface. A more plausible explanation is suggested by the abundance of permeable sand and gravel units along the contact with the overlying clayey tills of the Lagro Formation. The granular materials increase the bulk permeability near the top of the Trafalgar Formation, allow drainage of the till matrix to occur more readily, and thereby effect more rapid consolidation when the till is (or was) subject to increased confining pressure. As most of these granular units clearly post-date the deposition of the underlying till and its glacier, a more likely source of the hydrostatic stress required to cause the overconsolidation is the weight of the overlying sediments of the Lagro Formation, and possibly the ice that deposited them. Additional stress changes due to repeated wetting and drying associated with the pro-glacial environment are also likely to have been a major factor, as are post-glacial water-table fluctuations, particularly in the many places where the Trafalgar Formation is close to the land surface.

Discontinuities are planar openings or partings in sediment that separate the matrix into discrete blocks. Related terms include joints—openings across which there is no evidence of displacement; shear planes and faults—discontinuities showing definite evidence of movement of opposing walls; and fractures—which generally refer to any planar discontinuity without regard to displacement or origin. All of these features are commonly described in fine-grained glacial tills having relatively high cohesion, and they can cause the bulk engineering and hydrogeologic properties of the till to be very different from those of the matrix alone. The development of discontinuities at any given site in a particular unit can be complex and it appears that a variety of mechanisms are involved in their genesis and propagation.

Evidence from numerous exposures and boreholes indicates that discontinuities are widely present in the Lagro Formation, which encompasses the clay-rich surface tills of the basin. The discontinuities appear to primarily be of two types—moderately inclined shear planes and near-vertical joints. The shear planes commonly comprise groups of closely spaced, curvi-linear fractures that are generally inclined at angles between 20 and 50 degrees. At any given locality, they typically dip up-ice, opposite to the former direction of ice flow. Some of these features are associated with nebulous inclusions of highly folded lake sediment and virtually all bear slickensides and flutes that show that the top block was thrust over the bottom block. They are interpreted to result from shearing of debris-rich ice and subglacial sediment in areas of strongly compressive flow.

In contrast, the joints appear to be oriented in distinct sets that exhibit a strong conjugate pattern about local ice-flow direction (figure below). Joint spacing ranges from two inches to tens of feet and generally increases with depth. Joint lengths are typically in the range of one to 10 feet, although a few individual joints as long as 23 feet were observed. All of the observed joints were concentrated in the upper 25 feet of the till. There is abundant evidence of water movement through the joints, and seepage of water from large open joints was directly observed during wet periods. The till matrix adjacent to joints shows oxidation haloes as much as 2 feet wide, but is typically reduced (gleyed) immediately along the joint planes. Joint faces commonly show abundant deposits of calcite or gypsum. These observations, together with hydraulic and geochemical data from wells in the till (Fleming, 1994; Ferguson, 1992) suggest that the secondary hydraulic conductivity attributable to the joints is substantially greater than the primary hydraulic conductivity of the unfractured till matrix.

The joints in the Lagro tills have experienced a complex history. It is clear that they originated as shear joints in response to the stress field imposed by the overriding ice. However, most of the opening and propagation of the joints to their present depths probably did not occur until post-glacial time, in response to unloading caused by removal of overlying ice, and subsequent desiccation caused by lowering of the water table during warmer and drier climatic episodes. Post-glacial modification of the joints is strongly suggested by the relationship between the broad oxidation haloes, which probably formed above or within the zone of fluctuation of a formerly lower water table, and the apparently younger gleying of the joint surfaces, which has presumably formed in response to the high water table characteristic of the modern, wetter climate.



Rose diagrams showing relationship of azimuths of near-vertical joints in silty-clay till of the Lagro Formation to flow direction of the Erie Lobe at two sites in southern Allen County. Locations of sites 1 and 2 are shown on figure 3.

From "Glacial Geology" by Peter Fleming in Water Resources Availability  
in the Maumee River Basin

## Erie Lobe Terrains of Northeast Indiana

The general character and distribution of glacial terrains in northeastern Indiana closely parallels the three broad physiographic parts of the region noted earlier. It should also be noted that the region as a whole possesses a great diversity of terrains because of the varied glacial events that have affected it. Some of these are developed on sedimentary sequences other than the fine-grained ones that are the focus of this course, and are thus not covered here. This discussion emphasizes those terrains developed on fine-grained sediments of the Lagro Formation (figure 1).

The dominant morphological feature of the region as a whole is the series of arcuate end moraines that are broadly concentric about the Fort Wayne area (figure 1). These moraines generally mark significant marginal positions of the Erie Lobe at different times during the latest Wisconsin. From oldest to youngest they include: the Union City, Mississinewa, Salamonie, Wabash, and Fort Wayne Moraines, respectively. The Mississinewa and Wabash Moraines are by far the largest of these, forming robust, massive uplands up to several miles wide that stand as much as 100 feet above adjacent areas. The Fort Wayne Moraine is more variable in its physiography, ranging from a subdued ridge in parts of southern Allen County to a massive, rolling or hummocky upland in northeastern Allen County. In contrast, both the Union City and Salamonie Moraines are considerably less robust, mostly forming weak, discontinuous ridges.

All five of the moraines are conveniently subdivided into geographically and geologically distinct "northern" and "southern" limbs. In the southern part of the region, all five moraines generally constitute distinct zones of ridged topography separated from one another by extensive till plains of very low relief. North of the Wabash River and Maumee Lake Plain, however, the character of the moraines changes drastically. The three outer moraines lose their identities, coalescing into the massive morainal upland that has historically been called the Packerton Moraine (Wayne, 1963; figure 1). This upland dominates the northern half of the region and appears to be a complicated, polygenetic feature produced by stagnation of several different ice lobes. The Erie Lobe Moraines appear to be draped over older morainal topography and may be but a thin veneer at some places. Likewise, the Wabash and Fort Wayne Moraines merge into a broad belt of morainal topography north of Fort Wayne, where they are separated only by the narrow valley of the St. Joseph River.

These physiographic differences are mirrored by corresponding changes in sedimentary properties of the Lagro Formation, whose strongly asymmetric distribution is closely related to this condition. The unit appears to extend nearly twice as far to the southwest of Fort Wayne as it does to the northwest. In the southern part of the region, the Erie Lobe advanced over a substrate of very low relief, hence there was little to impede the flow of ice southwest out of the Maumee Lowland. The glacier moved chiefly by basal sliding and does not appear to have stagnated at any particular locality for a significant period, a fact evidenced by the almost complete absence of ablation topography within the till plain segments that separate the end moraines. In fact, scattered radiocarbon ages suggest that the ice front took significantly less than 500 years to reach its terminus at the Union City Moraine, a distance of some 200 miles from the western edge of modern Lake Erie. Deglaciation was characterized by steady, even retreat of the ice margin while the ice behind continued moving toward the margin by basal sliding. Consequently, deposition in this type of regime was concentrated at the base of the ice and resulted in thick sections of basal till, produced chiefly by the lodgement process. Large sections of the Lagro Formation in this region consist of basal till characterized by exceptionally well-developed lodgement fabrics and structures. The till plains are underlain almost entirely by basal till, locally capped by a very thin (0-5 ft) veneer of ablation sediment. Outside of stream valleys, what little relief that is present in the till plains is chiefly in the form of subtle, northeast-southwest trending rises that are the result of streamlining of basal till by the moving ice.

The end moraines mark locations where the ice margin became stationary for a considerable period and thus possess somewhat different, and generally more complicated, sedimentary sequences. The general pattern of deposition in these moraines is shown schematically in figures 2 and 3. It is important to note that only the ice margin was stationary during moraine deposition, while the ice sheet behind continued sliding forward and transporting sediment to the margin. Consequently, the cores of all of the moraines are composed of a substantial stack of basal till units that were sheared or thrust into place. This is particularly true of the proximal parts of the moraines (i.e., the side facing the glacier) as well as parts of the crest, where repeated overriding by the glacier occurred. In contrast, the distal (south-facing) sides of the moraines were generally located outboard of the ice margin and are thus dominated by mass movement deposits produced by sediment sliding off the ice front as well as by the remobilization of recently deposited basal till. Small bodies of basal till intercalated with the debris flows mark localized advances of small ice tongues out over the moraine. The combined thickness of the fine-grained sediments that core these moraines typically ranges from about 40 to 75 feet, but approaches 100 feet in the highest parts of the Mississinewa and Wabash Moraines.

Meltwater produced by the melting ice front was discharged out in front of each moraine. In some places, drainage was blocked by ice, sediment, or preexisting topography, creating proglacial lakes in front of the building moraines. Such instances are usually marked by bodies of fine-grained lake sediment that intertongue with the morainal sediments. In other instances ice-marginal drainage was well integrated and resulted in outwash deposition. In general, the Erie Lobe sediment load was dominated by silt and clay while having little sand and gravel; hence Erie Lobe outwash bodies tend to be relative small and fine grained. A particularly large sand body is present beneath and out in front of a large segment of the Mississinewa Moraine near Marion. This body is composed chiefly of fine to medium sand, attains thicknesses of 100 feet in some places, and may be a fan-delta whose lower part was deposited in a large lake whereas the upper part was deposited in a subaerial fan. This body is mostly capped by fine-grained sediment beneath the moraine, but it extends out under the Mississinewa River, where it appears to constitute the bulk of the "outwash" mapped in that part of the valley.

The above description applies mainly to those parts of the Erie Lobe end moraines that constitute distinct physiographic entities; i.e., chiefly south of the Wabash River. Conditions in the massive morainal upland that dominates the northern part of the region are substantially more variable, however. There, the Erie Lobe appears to have experienced extreme compression as it encountered older morainal topography and probably large blocks of ice left by earlier glaciers. This resulted in the transport of large amounts of sediment to the ice surface as well as probable stagnation of significant areas of the glacier. Sedimentary sequences are thus of a fundamentally different nature, consisting dominantly of a combination of mass movement and meltwater deposits that range in texture from clayey to sandy. These *supraglacial* sequences are somewhat analagous to the much thinner ablation deposits observed further south, but on a much grander scale. They are associated with moderate- to high-relief hummocky topography that is dotted with lakes, wetlands, blind valleys, and other features produced by melting of large stagnant ice blocks. Although basal till is present at some places, it is a relatively minor element in the near-surface of this area. Most of the clayey sediments that do occur at the surface appear to be a combination of debris flows or ice-walled lake deposits; they are generally highly heterogeneous and lack significant lateral continuity. The variability is compounded by the presence at or near the surface of older sediments of entirely different texture and origin in areas the Lagro Formation is thin or absent. For all these reasons, the environmental interpretations presented in subsequent sections are based mainly on the more uniform conditions to the south, and caution should be exercised when applying them to the northern part of northeastern Indiana. It should be pointed out, however, that the northern limbs of the Wabash and Fort Wayne Moraines are more like their southern counterparts, and most of the interpretations related to soil development and water movement are expected to generally be applicable to them.

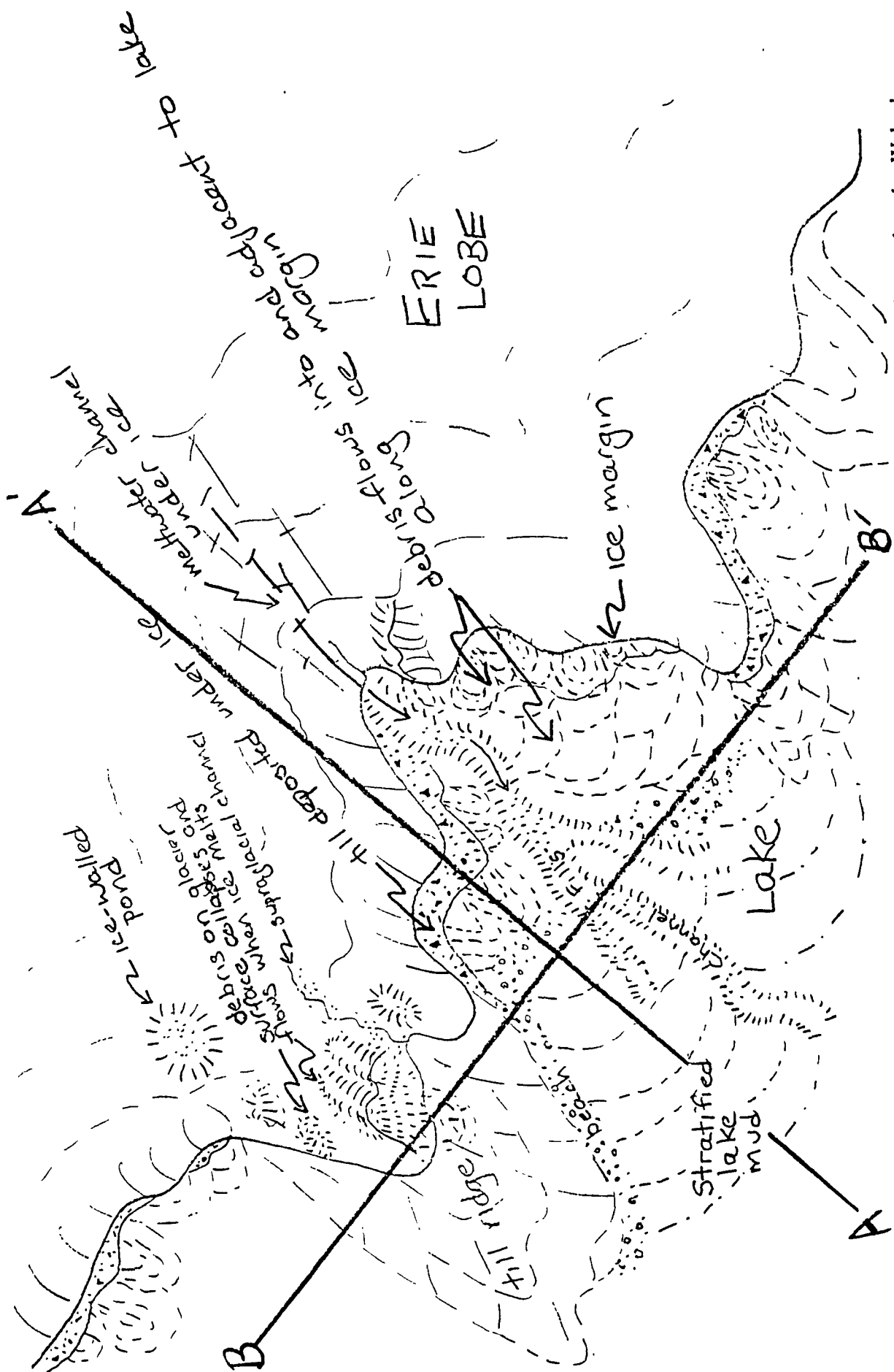


Figure 1. Schematic map diagram showing relationships of depositional environments when the Erie Lobe ice margin stood at the Wabash Moraine. Lines A-A' and B-B' are general locations of sections shown in figure 4.

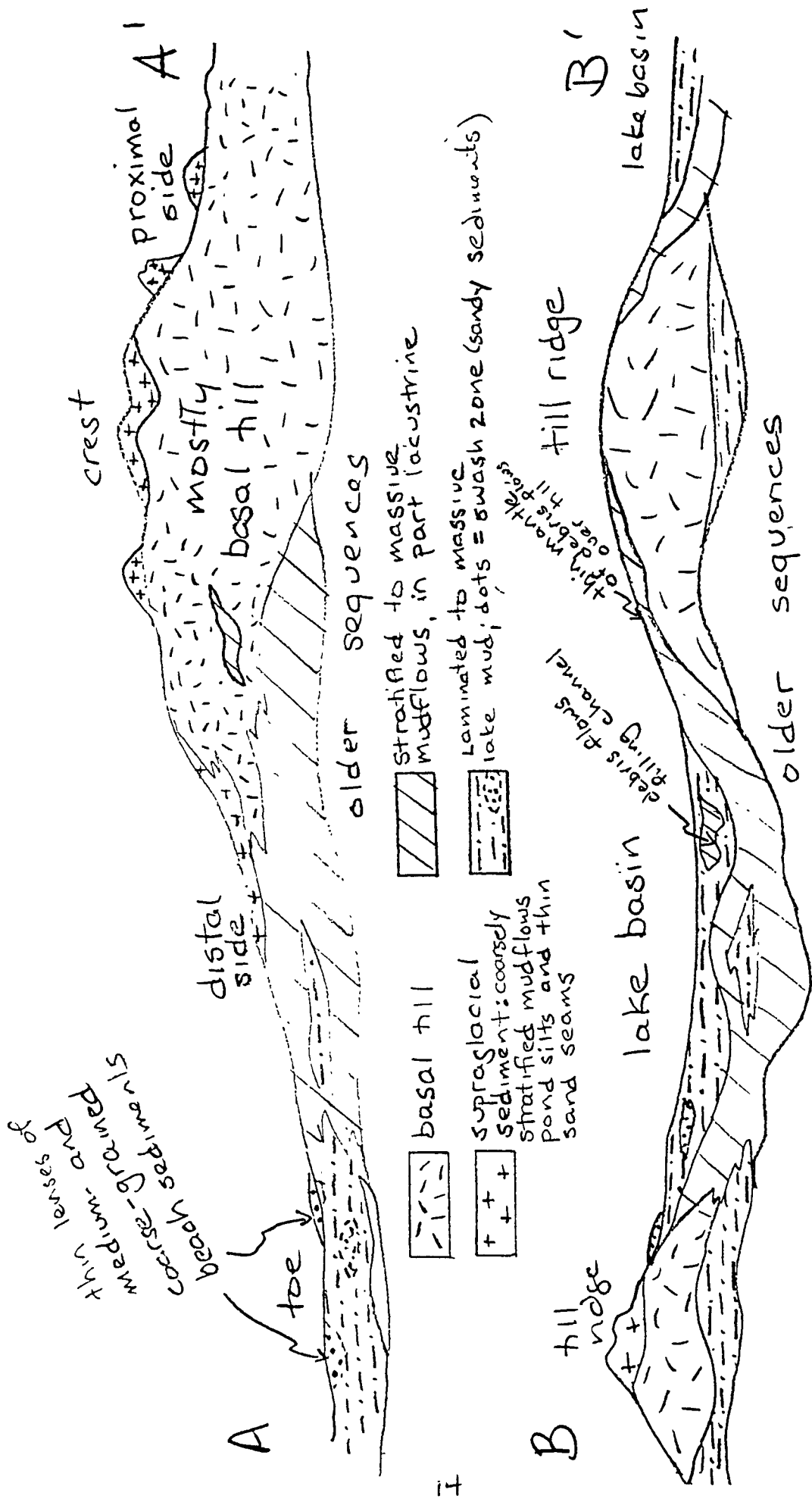


Figure 3. Schematic cross-sections showing relationships of depositional sequences to one another and to different parts of the Wabash Moraine. Section lines are shown in figure 3. Vertical scale is approximately 1 inch to 50 feet.

## History of the Erie Lobe and Significance of the Wabash Moraine

The late Wisconsin glaciation in northeastern Indiana is thought to consist of two major "episodes" (time) or "stages" (sedimentary sequences). Each "episode" actually involved up to several advances of any particular ice lobe that were relatively closely spaced in time. The first episode took place from about 22,000 to 16,000 ybp and produced the widespread loam textured tills that cover all of central Indiana and that occur at depth in northeast Indiana. This episode was followed by a period of general ice sheet retreat or stagnation during which large glacial lakes formed in most or all of the Great Lake basins. This period is widely called the Erie Interstadial, and a major phase of ancestral Lake Erie is thought to have covered an area much greater than the modern lake now occupies. Scattered remnants of thick lake sequences occur below the surface tills in Allen County and attest to the size of the lake. The second episode took place from about 15,500 to 14,000 ybp in Indiana (lasting longer further to the northeast). It was marked by widespread readvance of the Great Lake ice sheets, including the Erie Lobe, which advanced nearly to Muncie. The ice sheet advanced across the bed of ancestral Lake Erie and incorporated large quantities of lake mud into its basal load. Hence, regional till textures associated with this event are quite fine-grained relative to the earlier episode.

The Union City Moraine marks the maximum extent of the latest Wisconsin advance of the Erie Lobe and is thus properly called a terminal moraine. The other four moraines have historically been considered to be recessional moraines--i.e., places where the ice margin paused during its overall retreat from northeast Indiana. However, this traditional interpretation is probably incorrect. Gooding (1973) noted that surface tills of the Lagro Formation are markedly clayier atop and inboard of the Wabash Moraine than they are outboard. More recently, Fleming (1994) studied the structure of the Wabash Moraine in Allen County and concluded that the thick sequence of tills and other sediments that constitute both this moraine and the Fort Wayne Moraine are most likely from a distinctly younger ice advance relative to parts of the Lagro Formation outboard. Sediments outboard of the moraine are dominantly clay-loam in texture (figure 1) and may locally contain scattered sand bodies, whereas those inboard are predominantly silty clay to silty clay loam in texture and rarely contain any granular units. The inner sequence commonly overlies and contains sheared inclusions of lake clay, and it locally overlies erosional remnants of clay-loam till at depth in Allen County. All these characteristics indicate that the Wabash is a terminal moraine formed during a significant readvance of the Erie Lobe. Evidently, the ice front retreated a considerable distance back into the Erie Lowland prior to the readvance, during which time a lake formed and accumulated very fine mud in front of the ice. When the ice readvanced, there was little sediment available for the ice to incorporate other than extremely fine textured mud and till, hence its basal load was overwhelmingly fine-grained.

### Characteristics of the Wabash Moraine in Wells County

The descriptions presented below are based primarily on observations in approximately 25 soil pits excavated in various landforms of the Wabash Moraine in northern Wells County, as well as on the distribution of landscape elements and mapping of terrains within the moraine. These temporary exposures afforded a unique opportunity to document the nature and variability of near-surface sedimentary sequences in most of the major kinds of landscape elements that constitute the moraine, and to observe important differences in physical properties between sediments of different origin. In addition, extensive surface and subsurface data were collected from the moraine in nearby Allen County during a ground-water study of that county (Fleming, 1994), providing evidence for the geologic history, origin, and overall architecture of the southern limb of the moraine. The geologic framework and environmental interpretations developed from these investigations are believed to be typical of at least the southern limb of this moraine, and are also likely to be generally representative of conditions in the southern limbs of the other moraines as well. Their applicability to the northern parts of these moraines, especially the complicated Packerton Moraine, is less certain.



## *Sedimentary Sequences*

The sedimentary succession present at any given locality is referred to as a *vertical sequence*. The nature of the vertical sequence observed in a borehole or excavation records the type of depositional environment(s) that operated in that part of the depositional system. The entire depositional system in the Wabash Moraine is exceedingly fine grained; most of the sediment bodies observed were in the silty-clay-loam to clay range in the USDA textural triangle. Virtually all of these bodies are massive or poorly stratified, and they consist of poorly sorted mixtures of silt and clay with minor (generally less than 10%) amounts of admixed sand, pebbles, and larger rock fragments; i.e., sediment that would historically be called "till". Despite the overwhelmingly fine-grained character, there are significant distinctions in the texture, and especially the structure, of sedimentary bodies, that reflect important differences in depositional environment and the resulting distributions of geotechnical and hydrogeologic properties.

Four main types of vertical sequences were observed in excavations during the investigation, and their particular distributions generally correspond to specific landscape elements, which are described in the following section.

1) massive, poorly sorted, unstratified silty clay to silty-clay loam that contains as much as 10% rock fragments, mostly local dolomite and shale. Rock fragments are faceted (i.e. streamlined by moving ice), locally striated, and they are typically oriented, with most or all of the fragments in a given excavation having their long axes, striations, and (or) "pointed" ends aligned in a northeasterly direction. Scattered to closely spaced, near-vertical fractures as much as 3 ft or more in length were present in every exposure of massive silty clay. Many of these are oxidized, indicating downward movement of oxygenated ground water. The greatest soil development (to 30-35 inches) and thickest leached zones (up to 50 inches) observed during the investigation were found to be associated with this type of sequence. The massive silty clay (-loam) is interpreted as basal *lodgement* till, deposited by sliding ice at the sole of the glacier near the ice margin. Vertical sequences consisting chiefly of basal till were widely observed in exposures in the ramp, in some places on the crest, and rarely in small ridges on the distal face. Where observed on the face of the moraine, the basal till was commonly overlain by as much as 2-3 feet of crudely stratified silty-clay; the stratified sediments are debris flows derived from slumping of freshly deposited till during or shortly after deglaciation. Where the till ridges extend close to the toe of the moraine, thin till commonly overlies massive waxy clay, which is probably lake clay.

2) massive to somewhat thickly stratified silty clay loam containing thin pods and seams of silt and sand, and a considerable number of randomly oriented pebbles, cobbles, and boulders. The largest fragments are chiefly far-travelled granitic rocks from Canada. This sequence was observed in the only pit excavated on the crest of the moraine, on a small hummock. It showed poor soil development, no fracturing, and evidence of leaching to less than 20 inches. It is interpreted as *supraglacial* sediment, namely a chaotic mixture of debris flows, pond silt, and small fine-grained fills of ephemeral channels, all of which were produced by the let-down of debris on the ice surface when the glacier melted back from the moraine.

3) Crudely to moderately finely stratified silty clay with widely scattered rock fragments that are generally not oriented and sometimes concentrated along ill-defined surfaces or horizons. There appears to be little if any textural or compositional difference between adjacent strata; stratification is thus not obvious except where clayey partings were fortuitously exposed along the sides of pits by trenching action; the stratification is typically on the order of 0.3 to 2.0 inches in thickness. It locally shows evidence of slumping in the form of disrupted and contorted layers. In at least two pits, much larger lenticular bodies of silty clay loam appeared to fill distinct channels cut into the weakly stratified silty clay. No fractures were observed in any of these sediments, and soil profiles were typically very poorly developed to depths of less than 20 inches. Carbonates were rarely leached from depths greater than 14-15 inches, and films of precipitated carbonates

were commonly observed in a 1 to 3-foot-thick zone just below the leached zone. Most of the sediment below 10 inches was wet and gleyed, despite extremely dry surface conditions at the time of the fieldwork. This kind of sequence is dominant on the distal face of the moraine and was the most commonly observed of the four sequence types. This sequence is interpreted as a stack of *mudflows*, deposited in and just above a proglacial lake. The flows probably originated as subglacial debris, including till, that was released from the ice or that collapsed upon thawing and flowed downslope into the lake, where it spread out into lobes, or sheets of mud. Stacking of many such flows created a thick sequence of glaciolacustrine diamictons. Meltwater emanating from the ice front probably cut several channels in this material; some nearby debris flows evidently moved down these channels as viscous plugs, and are now preserved as the channel-like bodies of silty clay loam seen in some pits.

4) massive, poorly stratified, and laminated mud that contains few large rock fragments and interfingers with localized lenticular or blanket-like zones of muddy sand and granules. These sediments occur in and outboard of the toe of the moraine and may overlie sequences similar to #3 above. They were locally observed to interfinger with or to overlie mudflows. Soil development is poor and profiles are rarely leached more than 15 inches. Thick carbonate coatings are commonly present not far below the leached zone. No fractures were observed in these sediments. This kind of sequence is thought to be reworked lake-bottom sediments overlying debris flows. The finer grained, laminated mud was deposited in deeper water or under little wave energy; coarse-grained zones are former beaches and swash zones in shallow parts of the lake. At one pit along a former stream channel, some 3 feet of massive loam was present above lake bottom sediments. The loam is likely a combination of alluvium and colluviated silt derived from erosion of the adjacent moraine during cultivation.

#### *Landscape Elements*

Several distinct kinds of landform elements are consistently recognizable in and adjacent to the moraine (figure 4). These elements are associated with distinctive suites of sediment and thus constitute the basis for defining the different internal terrains of the moraine. From inboard (north) to outboard (south) these are:

1. the *ramp*, a gentle, north-facing slope that commonly shows some streamlining (elongation) of landforms parallel to former ice-flow direction. This terrain is also referred to as the "proximal" side of the moraine because it faces the direction from which the glacier advanced and was thus closest to the ice and in contact with its base. The ramp is the widest of the landscape elements and merges imperceptibly with the adjoining till plain that borders the north side of the moraine. It is typically underlain by basal till close to the land surface; a thin veneer of supraglacial sediment may be present atop the till at places.
2. the *moraine crest*, a broad, rolling to hummocky upland that forms the ultimate top of the ridge. At most places the crest is between 1/4 and 1/2 miles wide, and it includes several spurs, or ridges, of similar character and elevation that project southward from the main ridge. Near Zanesville the moraine exhibits a smaller, secondary crest north of the main crest; north and east of Bluffton, the crest widens dramatically, reaching widths of greater than 2 miles. In the latter area, the crest is less distinctly ridged, and is instead dotted with hundreds of small to medium hummocks and swales, forming a classic morainal landscape. The crest is typically underlain at depth by basal till, with the many hummocks being composed chiefly of supraglacial sediment.

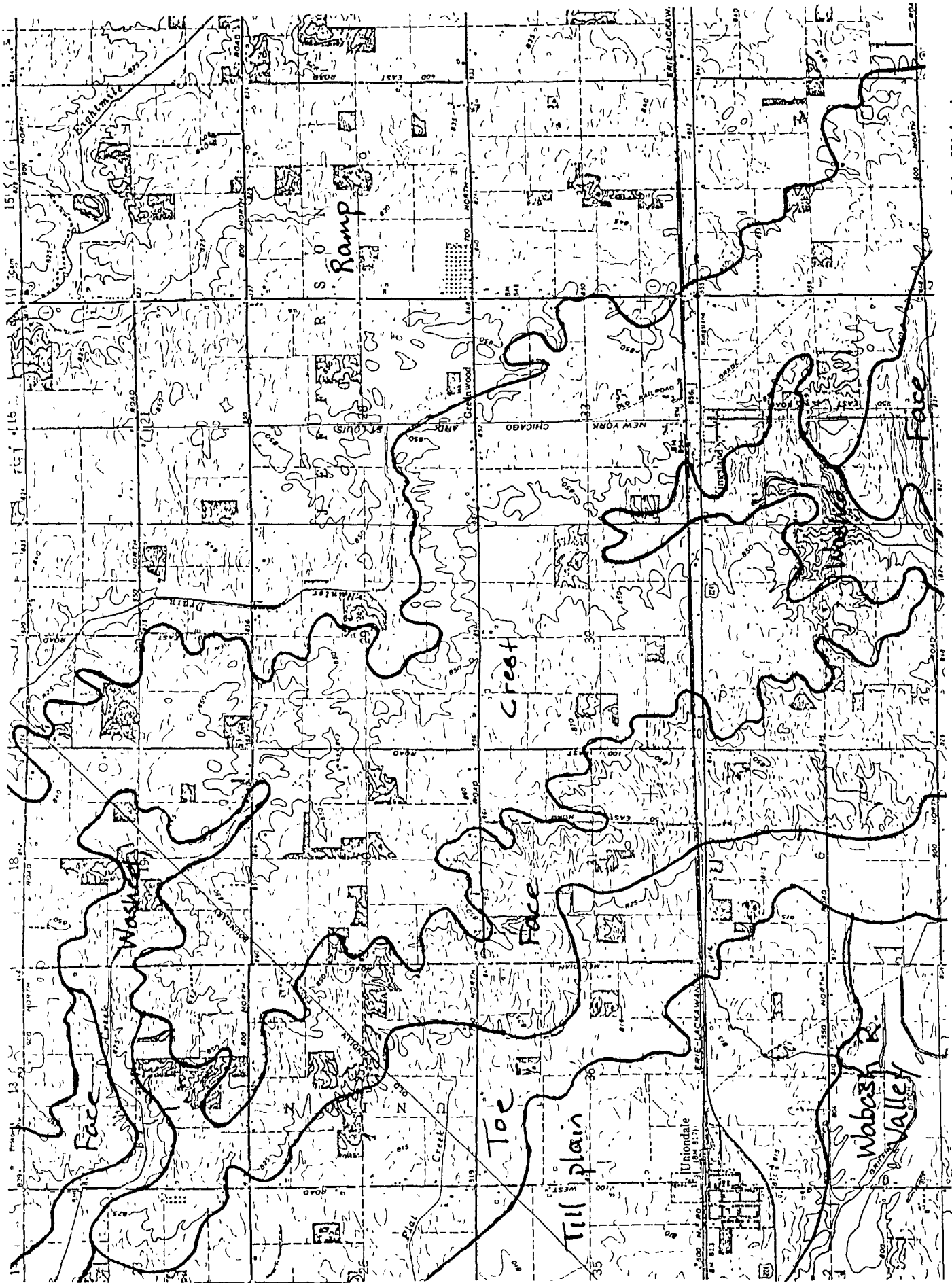


Figure 4. Section of the Uniondale 7.5-minute quadrangle showing topography associated with different landscape elements of the Wabash Moraine and adjacent areas in north-central Wells County. Contour interval: 5 feet.

3. the *face*, a somewhat shorter and steeper south-facing slope, also referred to as the "distal" side of the moraine because it faced away from the glacier and was thus more distant from the ice and rarely in direct contact with its base. The face is commonly dissected by numerous short, steep ravines and is locally punctuated by small hills and ridges, including a number of small but prominent spur ridges that extend into this terrain from the main moraine crest. It is underlain mainly by proglacial mudflows deposited off the front of the ice, although basal till may also be present close to the surface beneath the spur ridges that extend into this terrain from the main moraine crest.
4. the *toe*, a very gently sloping to virtually flat region immediately in front of the face. This region is present only along the northwestern half of the moraine in Wells County and is crossed by several small streams. The toe was the site of proglacial lakes and ponds, hence it is commonly underlain by various combinations of lake mud and mudflows. A blanket of loamy colluvium and alluvium is typically found adjacent to streams and locally reaches thicknesses of five feet. The alluvium and colluvium are likely to exhibit the best permeability of any of the fine-grained sediments.
5. *Washed areas*, which are associated with the channels of the larger streams that emanate from the face of the moraine or that parallel its toe. Most of these features represent former meltwater channels that were active when ice stood at the moraine. Washed areas typically create strongly dissected topography where they cut the crest and face of the moraine, and may be flanked by steep slopes. They are likely to be similar to adjacent terrains in terms of underlying sequence, although they may commonly be veneered by alluvium and colluvium, or even by small terraces of sandy outwash along some of the larger streams, such as Eightmile Creek.
6. The *Wabash River Valley*, which parallels the front of the moraine in the southeastern part of Wells County. In this area, the valley lies up against the face of the moraine, producing considerable relief and extensive dissection of the moraine by numerous short tributary ravines. The valley is generally underlain by loamy or sandy alluvium and some sandy outwash, which commonly overlie limestone bedrock at relatively shallow depths. The Wabash functioned as the principal ice-marginal channel carrying meltwater from the ice front when the moraine was formed.

In most of the map area, the moraine is a relatively simple ridged upland some 1 to 3 miles in width and standing some 40-50 feet above adjacent areas, across which the above terrains form a relatively orderly progression. Within an approximately 5-mile-long segment in the Uniondale and Bluffton 7.5-minute quadrangles, just north and east of the City of Bluffton, however, the character of the moraine changes considerably, broadening to as much as 5 miles in width and locally standing some 75 feet above the adjacent Wabash River Valley. Although the basic terrain elements outlined above are recognizable here, the form of the moraine crest is considerably more amorphous, being less distinctly ridged and instead dominated by innumerable hummocks, swales, and depressions. Hummocks and small ridges also extend into both the face and the ramp in this segment. The appearance of this segment suggests that a considerable amount of supraglacial sediment may be present in the near subsurface, mainly within the many hummocks.

Because depositional environments shifted through both time and space during construction of the moraine, it is problematic to predict the *exact* type of sediment that will be present at a specified depth at a particular site. As noted above, however, the distributions of particular kinds of sedimentary *sequences* do correspond fairly closely to the different landscape elements of the moraine, thus providing some basis for forecasting the likely range of conditions that might be expected beneath a particular area of interest.

## ENVIRONMENTAL INTERPRETATION

### Macroporosity in Fine-Grained Soil and Sediments

Several onsite systems located on the Wabash Moraine in Wells County are known to perform poorly or to have failed completely, and there are probably other systems with similar problems here and elsewhere on the moraine. The permeabilities of the fine-grained sediments and of the soils characteristically developed on them are known to be quite slow in most cases (e.g., Fleming, 1994; Kirschner and Zachary, 1969). On the other hand, there does not appear to be universal failure of systems throughout the moraine, nor on nearby till plains composed of similarly fine-textured sediment, so it seems reasonable to conclude that localized soil-geologic conditions are responsible for the most extreme problems with onsite systems, and that these factors are at least partly related to the type of soil parent material and its effect on soil development and water transmission.

Characteristics observed in the test pits that appear to be of particular significance to the problem of poor septic performance in this setting are listed below:

1. The sediments in most pits exhibited a considerable moisture content at depths greater than about 10 inches. Despite a lack of appreciable rainfall for several months leading up to the investigation, some samples appeared to be close to saturation, even on uplands.
2. Virtually all of the pits showed poor soil development, except those sequences dominated by basal till. Poor soil development was evidenced by lack of an E horizon, lack of topsoil (probably due in part to poor cultural practices resulting in erosion), coarse subsoil structure, lack of granular structure below the Ap horizon, and very limited zones of leaching of carbonate minerals, typically 15-20 inches or less. The translocated carbonates were almost invariably reprecipitated not far below the leached zone, typically forming thick, prominent coatings on ped faces.
- 3) Many pits exhibited a near-surface, virtually impervious "hardpan", commonly within a foot or two of the surface. This condition was typical of vertical sequences 3 and 4 above and may be partly attributable to loss of topsoil by erosion coupled with repeated plowing of the remaining upper layer.
- 4) In contrast, test pits in basal till showed considerably better soil development. Carbonates were leached to depths of 35-50 inches, a better-developed structure was typical of the subsoil, and the translocated carbonates were commonly reprecipitated at depths of 60 or more inches. Significantly, fractures showing evidence of water movement (e.g., oxidation haloes, calcite and(or) gypsum films on fracture faces) were observed in the till but not in other kinds of profiles.
- 5) Sequences consisting chiefly or entirely of basal till were observed mainly on the proximal side (ramp) and crest of the moraine, and only rarely on the distal side (face), where the till, if present, was typically thin and associated with other kinds of fine-grained sediments.

Items 1-3 above are indicative of severely limited vertical water movement, and suggest that the majority of infiltrating precipitation moves laterally along the top of one or more "limiting layers". The most common kind of limiting layer is the "hardpan" or "plowpan" noted in item #3 above; however, limited depth of the soil development and the absence of macropores in parent material results in the shallow, unweathered parent material also acting as a limiting layer. Consequently, water movement is dominated by lateral flow in the plow layer. The ubiquitous precipitation of translocated carbonates at relatively shallow depths is further testimony to poor permeability; such an abundance of these precipitates is rare in adequately drained soils in humid environments. Their presence suggests that much of the water that infiltrates the soil is removed by evapotranspiration, causing remaining pore waters to be supersaturated with carbonates in solution at shallow depth.

Direct observations made in soil pits near failing systems, as well as anecdotal evidence concerning ground-water flow patterns in the Lagro Formation from other localities suggest that the explanation may in part lie with the relative development of *macroporosity* in the different kinds of fine-grained sediment bodies. Macropores may be of geologic or biologic origin and include all those openings that create an interconnected permeability network that leads to elevated *secondary hydraulic conductivity* (see box on **Hydraulic Conductivity of Glacial Till and Its Measurement**). Examples of macropores in fine-grained sediments include joints, fractures, small sand seams, root channels, and burrows.

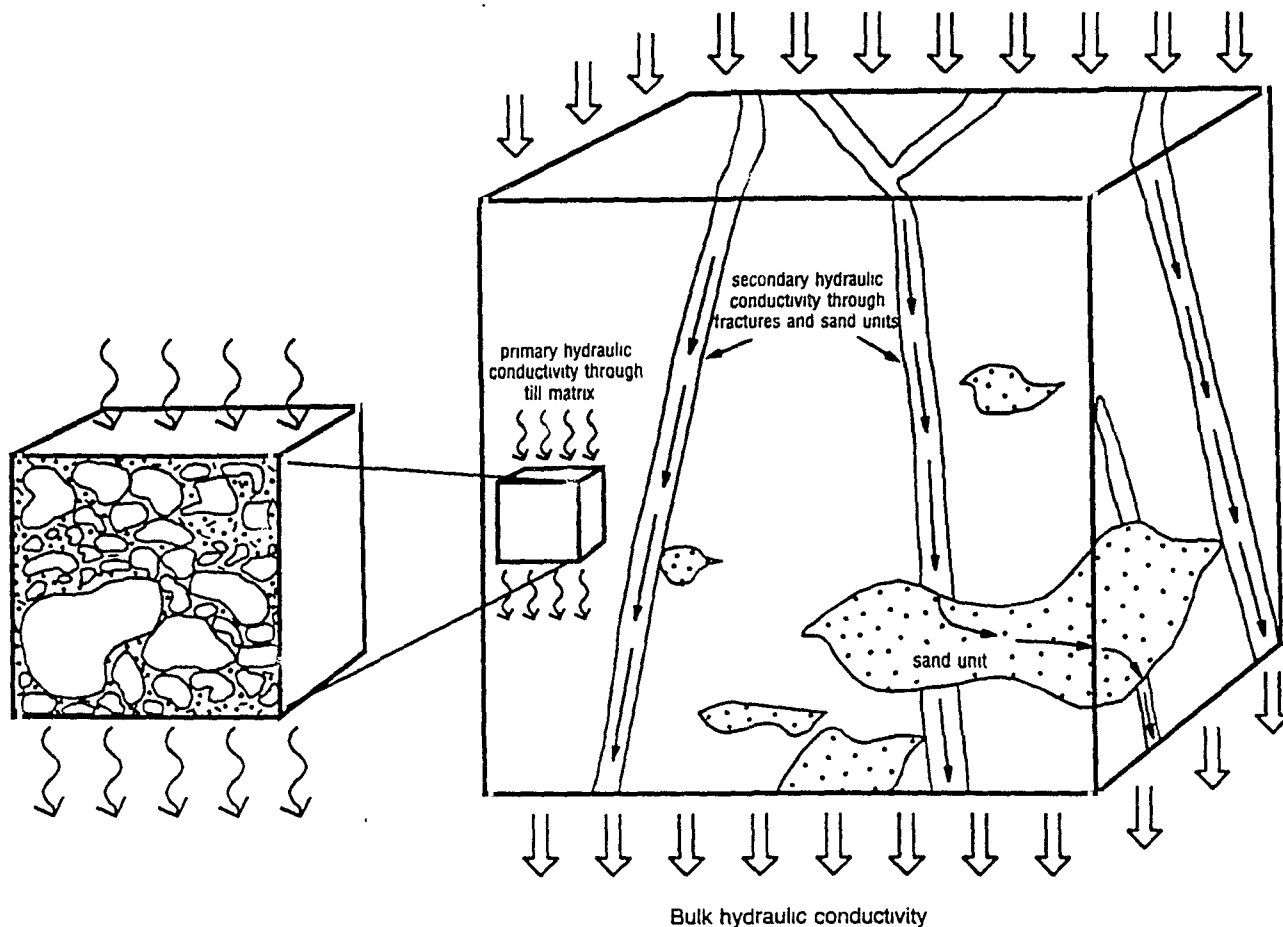
Studies of ground-water flow in tills and related sediments in northeast Indiana and elsewhere offer additional anecdotal evidence bearing on this situation. It has been increasingly recognized in recent years that water movement in fine-grained glacial sediments is largely controlled by the presence, origin, and frequency of macropores. The primary hydraulic conductivity of clayey diamictons and lake sediments, such as those at the sites in question, is typically  $10^{-8}$  cm/sec (less than one inch per year) or less; in some lake clays, it may be less than  $10^{-10}$  cm/sec (Stephenson and others, 1988). In contrast, the presence of a systematic fracture system can greatly elevate the bulk hydraulic conductivity of these sediments, sometimes by several orders of magnitude. Several field studies have illustrated this relationship (see Stephenson and others, 1988, for a summary). For example, it is well known that most soils developed on clayey glacial sediments are poor candidates for irrigation; in fact, irrigation of these soils can harm their fertility by leading to excessive saturation and buildup of salts and carbonates. Hendry (1982) has shown that this is NOT the case in till soils where extensive fractures are present. In those instances, fractures in the parent material appeared to increase soil drainage greatly and may have led to better soil development.

Fractures in glacial sediments are most commonly the result of two conditions:

- 1) shear stress caused by overriding ice during or after sediment deposition. In this situation, most fractures tend to develop in two conjugate sets oriented at about 60 degrees to ice flow (see earlier box on **Geotechnical Properties of Erie Lobe Tills...**). Many basal tills experience this condition and may exhibit systematic fracturing, but such fracturing has also been seen in lake sediment and other clayey deposits that were subsequently overridden by ice;
- 2) stress relief caused by repeated shrink-swell, wetting and drying, or unloading due to removal of overlying or supporting sediment. In this case, fractures tend to be randomly oriented, but may form desiccation polygons, similar to cracks in recently dried mud.

The process most conducive to the development of extensive fractures at the sites in question appears to have been overriding of sediment, chiefly basal till, by ice. On the Wabash Moraine, this condition mainly occurred on the proximal side (ramp) of the moraine, and locally along the crest. In contrast, there appears to have been little or no overriding of sediments at most places beyond the crest, nor other known mechanisms to promote the development of significant macroporosity. Consequently, soil development and water movement are severely hindered in parent materials lacking the macropores needed to promote drainage, root penetration, leaching, or translocation of fine particles and carbonates. On the other hand, soil profiles in test pits developed in till are deeper and better developed; soil profiles show strong prismatic structure, and conceivably the orientations of many ped faces may be sympathetic (parallel to) fractures in the parent material. In short, relations observed at these sites suggest that fractures are the most likely reason for the markedly different soil development and water movement in till soils versus those developed in other types of fine-grained sediments.

### Hydraulic Conductivity of Glacial Till and its Measurement



The hydraulic conductivity of glacial till can be of several types, depending on both the mode of deposition and postdepositional history of the particular unit in question, as well as the scale of measurement. Till is composed of an unsorted mixture of particles that range in size from clay to boulders. Till is deposited directly by glacier ice and is characteristically **overconsolidated**, due to the great weight of the overlying ice. Depending on the particular dynamics of the glacier during till deposition (stagnant or active) and the distribution of meltwater within the glacier, till may contain sand and gravel bodies that range from tiny layers a few millimeters thick to extensive channels tens of feet thick and hundreds of feet in length. In general, most till units contain some sand and gravel bodies, but in most places they are commonly small and isolated from one another.

The **primary hydraulic conductivity** is attributable to the matrix of the till. Because of its poorly sorted and overconsolidated nature, the primary hydraulic conductivity of fine-grained till is typically among the lowest of all

unconsolidated sediments. This attribute has made till an attractive target for waste disposal sites because it is widely believed that the low primary hydraulic conductivity will prevent or at least greatly limit the migration of contaminants from these sites.

Hydraulic conductivity is scale-dependent, however, and many tills exhibit appreciable **secondary hydraulic conductivity** related to the presence of more permeable zones within it. Perhaps the best-known cause of secondary hydraulic conductivity is fractures. The origin of fractures in till is debatable, but in some units they form a well-connected network that essentially controls the majority of ground-water movement. The hydraulic conductivity of fractured tills ranges from ten to as much as 10,000 times greater than their unfractured counterparts (Stephenson and others, 1988). Secondary hydraulic conductivity may also be attributable to very small layers and seams of sand within the till, some of which may be difficult to see without careful inspection. Although the sand seams represent a different and better sorted

material, they typically originated with the till during deposition and, for all practical purposes, are an integral part of the till unit.

The combination of primary hydraulic conductivity and secondary hydraulic conductivity associated with all of the fractures and sand seams within a large (many cubic meters) volume of till represents the **bulk hydraulic conductivity**. The value of bulk hydraulic conductivity usually falls somewhere between primary and secondary hydraulic conductivity. If the sand seams and fractures are large and collectively form a well-interconnected network that extends completely through the volume of till, then bulk hydraulic conductivity will be similar to secondary hydraulic conductivity. On the other hand, if the secondary features are small and essentially act only as isolated reservoirs, then the bulk hydraulic conductivity will more closely approximate primary hydraulic conductivity.

Hydraulic conductivity is measured in a variety of ways, all of which are scale-dependent. The most common laboratory method employs a device known as a permeameter, which places a hydraulic gradient across a small sample of till within a cylinder, and measures either the rate of water flux or the hydraulic head differential. There are several variations on this device; probably the most useful of these is a flexible-wall permeameter, which can measure the permeability of a relatively large, undisturbed block of material, which is likely to be more representative of actual field conditions. In contrast, many permeameter measurements are made on disturbed samples derived by disaggregating a block of till and then repacking it into a fixed-wall cylinder. This procedure typically underestimates the hydraulic conductivity because it does not take into account any secondary features and may also misrepresent the original arrangement of grains in the till matrix.

A common field technique is the slug test, which measures the response at a single well to adding or subtracting a known volume (slug) of water. Although it has certain limitations, the larger scale of this method is more likely to detect secondary hydraulic conductivity, which is usually associated with features too large to be represented in a typical laboratory sample. A wholly different type of field method operates at a much larger scale by utilizing measurements of selected natural and manmade radioactive isotopes (such as radiocarbon, oxygen, tritium) to estimate the age of ground water at different depths. Under favorable conditions, this approach yields very precise estimates of vertical hydraulic conductivity because the time of recharge of ground water at different depths is known. This geochemical technique is probably the most representative measure of bulk hydraulic conductivity, because it averages the effects of both primary and secondary hydraulic conductivity over a scale of tens or hundreds of cubic meters.

### Ground-Water Flow Velocity in the Lagro Formation

There is direct evidence supporting the importance of macropores to ground-water flow rates in the Lagro Formation. In 1990, the IGS installed a series of monitoring wells nested at different depths in the Lagro Formation and in underlying tills and bedrock in order to characterize rates and mechanisms of recharge through this typical confining sequence. The well nest is located on the ramp of the Wabash Moraine in southern Allen County, not far from an exposure of the same geologic sequence in a nearby limestone quarry. The Lagro Formation below the well site is 55 feet thick and contains a thick section of basal till. The wells have furnished a variety of useful data, including short- and long-term water-level behavior, geochemistry, environmental isotopes, and physical properties of the sediment.

Geochemical and environmental isotope data (Ferguson, 1992; Ferguson and others, 1991) indicate that the bulk of the ground-water within the upper 37 feet of the Lagro Formation is no more than 145 years old and may be as young as 45 years. Tritium data suggest that most of the water above 20 feet is recent. The response to precipitation events of wells screened at and above 27 feet is rapid and sharp, indicating significant vertical hydraulic conductivity. In contrast, the response of deeper wells to individual precipitation events is considerably slower. Likewise, water levels in the shallow wells fall sharply during dry periods, whereas those at depth do not fluctuate dramatically. The data indicate that average vertical ground-water velocity below the site is between 0.3 and 1 foot per year, with the vertical hydraulic conductivity in the upper, fractured part of the till being  $10^{-5}$  cm/sec or greater. For comparison, triaxial permeameter tests on unfractured blocks of this till yield hydraulic conductivities on the order of  $10^{-8}$  cm/sec.

The water-level behavior and geochemical features at the well site are consistent with the observations at the nearby limestone quarry.



There, the Lagro Formation is about 35 feet thick, consists mainly of lodgement till, and is strongly and systematically fractured in the upper 20-25 feet. Large, near-vertical, open fractures up to 20 feet long are evident, and commonly seep ground water during wet periods. The largest fractures have oxidation haloes 12 inches wide at depths of 15 feet, and many joint faces are encrusted with gypsum or calcite deposited by ground water. Visible fractures appear to extend to a maximum depth of about 25 feet; conceivably fractures may exist at greater depth but are not open because of the confining stress. The soil profile above the fractured till is developed to a depth of 50-60 inches. In contrast, lower parts of the till (below about 25 feet) are massive, unfractured, and exhibit reduced soil colors.

#### Implications for Septic System Performance

Geologic conditions in many parts of the moraine are not likely to promote satisfactory septic system performance; in fact, they are entirely inimical to it. This is evident in the common failure of systems installed on the moraine. It seems likely that few, if any systems installed on unfractured sediments anywhere along the distal side of the moraine, or in the lake sediments at its toe, will perform properly, at least in the intermediate- to long-term. Some of the systems we have investigated malfunctioned immediately, generally manifested by a complete lack of flow in the household plumbing and in some instances, surface failure.

Somewhat better performance may be possible in the till-derived soils typically found on the proximal side of the moraine and locally along the crest, because of their greater macroporosity. It must be emphasized that appearances are relative, however. Despite the apparently greater degree of soil development and water movement in the till soils, they must still be considered "severely" limited for septic systems. In other words, we are comparing something that has essentially no vertical permeability (thin, poorly developed soils on lake clays and silty-clay debris flows) to something having extremely low permeability by any standard (clayey till soils). This fact is evidenced by the widespread use of sand mounds in Allen County, where this same depositional system covers better than 50% of the territory. Nevertheless, sites underlain by till or other fine-grained sediment having significant macroporosity may be reasonable candidates for systems characterized by large absorption fields and extremely low loading rates. In any event, knowledge of the presence or absence of macroporosity in the parent materials below a given site may affect the choice of different kinds of systems, loading rates, etc.

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