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A Fracture Analysis of Glacial Tills in Southwest Michigan

Ralph L. Freed

Western Michigan University

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A FRACTURE ANALYSIS OF GLACIAL TILLS
IN SOUTHWEST MICHIGAN

by
Ralph L. Freed

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
Kalamazoo, Michigan
June 1993
Fractures were recorded and measured at seven southwest Michigan glacial till locations to identify geometry and spacing. Strong preferred orientations were shown at azimuths of 110° and 140° for two sites, and at azimuths of 85°, 110°, and 135°, and at 44° and 167° for two sites. Several sites had numerous oblique fractures.

Thirty-eight azimuthal Wenner arrays and four Schlumberger surveys show apparent resistivities vary widely with depth of penetration and material composition. Eleven percent of azimuthal surveys show an elliptical data array coinciding with preferred orientation of an adjacent fracture set. The relationship between azimuthal survey and fractures is due to the paradox of anisotropy.

Successful correlations were not always accomplished due to anthromorphic structures such as buried cables or sewer systems. Dry conditions during part of the work decreased electrode contact and increased apparent resistivity values, and the paradox of anistropy did not apply when overburden was greater than roughly five times the "a" spacing used.
ACKNOWLEDGEMENTS

Many people helped me with this work, and I dedicate this thesis to them.

I thank my committee members—Ronald Chase, Gerry Clarkson, Richard Passero, and William Sauck—for their advice and their time. Jiro Wada was a diligent worker who helped me complete my field work, as were others who aided me in my work.

I also wish to express my appreciation to my wife, Antoinette, for word processing, technical communication, and her patience for putting up with me for the last six years.

I thank my daughter, Emily, for patiently waiting for her Dad to finish his graduate work before he could play with her.

Most importantly, I wish to thank Mr. P. Bear for his invaluable technical assistance and unswerving faith.

Ralph L. Freed
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A fracture analysis of glacial tills in southwest Michigan

Freed, Ralph L., M.S.
Western Michigan University, 1993
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For many years geologists assumed that the deposition of hazardous and unwanted materials in till, because of a till units' low permeability, would isolate hazardous materials from the environment and protect people from its deleterious effects. The discovery of fractures in till cast doubt on the idea that till has permeability sufficiently low to act as a confining layer.

Fractures, also called joints, are structures resulting from brittle behavior in which blocks of rock are not displaced relative to one another across a planar discontinuity (Hobbs, Means, & Williams, 1976). Fractures increase the porosity and permeability of rock and till units by allowing water to move through the matrix. Increasing the porosity and permeability allows fractured rock units to be used as aquifers while decreasing the ability of clay tills to act as confining layers for hazardous waste.

The importance of fractures in influencing the hydrogeologic properties of rocks has been known since the turn of the century (Fuller, 1905; Ellis, 1909), when fractures were determined to increase the water-bearing
capability of crystalline rocks. Horberg (1952) first observed till fractures in the upper 3-4.6 meters of a till in the Canadian Plains of Alberta. Fractured tills have been described in the glaciated regions of Canada (Horberg, 1952; Hendry, 1982; Grisak, Cherry, Vonhof, & Blumele, 1976; Grisak & Cherry, 1975); Iowa, Kansas, Missouri, Nebraska (Sharp, 1984); Wisconsin (Fleming, 1986; Connell, 1984), Michigan (Chase, 1988); and New York (Prudic, 1982).

Recent studies show (a) fractures in tills can greatly alter the deposits' hydraulic conductivity and storativity by allowing more fluids to move through the till (Grisak & Cherry, 1975), (b) fractures can alter the bulk permeability over the matrix permeability by several orders of magnitude (Keller, van der Kamp, & Cherry, 1985), (c) isolation of surface contaminants from aquifers may not be possible due to fractures in the underlying unweathered till (Keller et al., 1985), and (d) fractures increase the median in situ hydraulic conductivity by three orders of magnitude over the predicted laboratory permeability tests, requiring a landfill site to be excavated and the fractured clay compacted (Gordan & Huebner, 1983).
Purpose of the Study

The premise of this study is that a resistivity survey can be used to determine the intensity and orientation of fractures in the till. If the intensity of the individual fractures could be determined, fractured till could be identified. A determination of the orientation of the fractures would affect the direction of flow of a contaminant plume. One should be able to determine fracture intensity and orientation in till with a resistivity survey.

Taylor (1984) used the azimuthal resistivity survey to successfully determine the porosity of bedrock in Wisconsin. Fleming (1986) continued this work, both in bedrock and till in Wisconsin, and found some success in defining fractures in till. This study expands the use of this technique from bedrock to glacial till. If the azimuthal survey could be used to define fractures in till, the azimuthal survey could be employed to determine the permeability of tills, with the resulting information used to site landfills.

The study area was chosen for the following reasons: proximity to the university, large outcrops of till with exposed fractures, an existing fracture study (Chase, 1988), and the availability of relatively large expanses of open area. Most azimuthal surveys were conducted near
areas where fractures were observed (Chase, 1988); however, the North Beach site was chosen to explore any preferred orientation in sand. The Briarhills site was a construction site where fractures were measured and the field site was chosen because of the large expanse of open area.

Location

The study locations are situated as follows: eight in Allegan County and two in Van Buren County (Figure 1). Because of the large numbers of surveys that were conducted, special definitions to aid in keeping track of the geographic relationships were devised. A survey is a distinct individual geophysical event. A site is the center point of a survey and more than one survey may be conducted at that site. Locations are large areas, up to several acres in size, where more than one site is located. The exact positions of specific locations and sites are listed in Appendix B. Locations are named for the owner of the property at the time of the survey or for a local topographic feature. Locations on the beach have a letter value corresponding to a fracture analysis site. At a particular location, there may be more than one site where geophysical surveys were conducted, with more than one survey conducted on an individual site (Appendix B).
Figure 1. Site Location Map.
Each site was assigned an alphanumeric value. The letter was arbitrarily chosen, and the number gets larger with increasing distance from the bluff at Lake Michigan; at the Brandl location, there are 5 sites with 13 surveys. The number 1 is reserved for sites on the edge of the cliff. Site classification is not used if there is only 1 site per location.

Most locations correspond to sites where structural analyses of fractures had been made (Chase, 1988). Locations in Van Buren County reflect the homogeneous nature of the dune sand at North Beach and the underlying fractures at a construction site.

**Climate**

Southwestern Michigan's climate is continental, with cold winters and warm summers. Data from U.S.D.A. Soil Conservation Service supports this (Table 1).

**Table 1**

<table>
<thead>
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<th>Temperature and Precipitation Values for Allegan and Van Buren Counties</th>
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<td>Allegan</td>
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<tr>
<td>July high</td>
</tr>
<tr>
<td>July low</td>
</tr>
<tr>
<td>Jan. high</td>
</tr>
<tr>
<td>Jan. low</td>
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<td>precipitation*</td>
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*Average annual precipitation in inches.*
The greatest influence on weather in southwest Michigan comes from Lake Michigan. Areas proximal to the lake have gentler summers and harsher winters than inland areas. Lake effect precipitation creates a snow belt inland from Lake Michigan, extending approximately as far east as western Kalamazoo County.

Scope

Areas of investigation were the southwestern Michigan counties of Allegan and Van Buren (Figure 1). During the summers of 1987, 1988, and 1991, 39 azimuthal resistivity surveys were conducted using Wenner arrays, and 4 depth soundings were conducted using Schlumberger arrays. Work began with clay tills near the bluffs of Lake Michigan, then moved to a beach, and was completed in fields away from the cliff. Two conditions needed to conduct fracture surveys were (1) areas good for fracture analyses and azimuthal surveys, and (2) totally saturated fractures. It was not always possible to find locations fitting the first requirement. Bluffs on Lake Michigan were needed for fracture observation along with a nearby field to conduct the survey in; however, homes were often built on top of the bluffs above fracture locations, physically limiting space in which to conduct a survey, with utility and septic lines to interfere with the
results of the survey. At the start of the research, fractures were saturated, but the summer of 1988, when most of the research was conducted, was an extremely dry season. Normal precipitation levels for June, July, and August in Allegan County are 3.90, 3.21, and 3.34 inches, respectively; during the summer of 1988, precipitation levels for the month of June, July, and August were 0.9, 1.91, and 1.94 inches, respectively.

Previous fracture analyses had been conducted by Chase (1988) at locations along the bluffs at Lake Michigan. As part of this study, resistivity surveys were conducted, when possible, at locations adjacent to these fracture analysis sites.

Geology of Lake Border Moraine

The Lake Border moraine is a complex moraine system which stretches from the head of Lake Michigan northward through the highlands of the northern portion of the Lower Peninsula, around Saginaw Bay, and down the eastern slope of the thumb. However, in places, the Lake Border moraine is intricately associated with earlier and later systems, and it is not clearly differentiated from other systems. Only in the southern portion of the Lake Michigan basin is the Lake Border moraine the innermost moraine system (Leverett & Taylor, 1915). The Lake Border
moraine alternates between intersecting Lake Michigan and being located inland away from the lake (Figure 1).

The stratigraphy of the Lake Border moraine (Monagham, 1988) consists of three till units separated by lacustrine deposits of sand or silt. The Glen Shores till, exposed at the lake level, is composed of 46 percent sand, 34 percent silt, and 20 percent clay. The till is locally intruded from below by clay diapers and contains small pieces of wood. The Glen Shores till dips below the present beach near the development of Glenn Shores and is not observed elsewhere along the Lake Michigan shoreline.

The Glen Shores till is overlain by 5-10 cm of discontinuous gravel, and up to 2 meters of sand and laminated silt. Organics from both the gravel and sand/silt deposits have been radio carbon dated from 37,150-48,000 years B.P.

Above these sand and gravel layers lays the massive blue-gray sandy Ganges till. The till is from 5-6 meters thick near the described section, but ranges from 0-6 meters along the shoreline. The Ganges till is composed of 59 percent sand, 22 percent silt, and 19 percent clay with scattered pebbles, cobbles, and boulders. There are 1.5-1.8 meters of lacustrine sand which overlays the Ganges till; the contact between the two is sharp.
The third till, Saugatuck till, is roughly 2.5 meters thick and consists of 36 percent sand, 42 percent silt, and 22 percent clay. The lower contact is sharp with the upper contact gradational through 0.3 meters of reddish-brown silty clay. Deposits elsewhere correlated to the Saugatuck till are believed to be a mixture of subaqueous debris flows and lodgement tills (Larson & Monaghan). The Saugatuck till measures approximately 3 meters at the described section but ranges from 0 to 20 meters throughout the Lake Border moraine. The section is topped with 3-4 meters of lacustrine sand of the Lake Chicago stage.

The above stratigraphy represents one section of the Lake Border moraine west and south of the town of Glenn near the development of Glenn Shores. As one moves away from this section, the sandy layers thin and thicken significantly, appear locally not in the same stratigraphic position, and are absent from the stratigraphy in some places (Chase, 1988).

A particle analysis performed on the Ganges till (Chase, 1988) also revealed the material to be less sandy and silty and composed of more clay particles than the studies by Monaghan.
CHAPTER II

INTRODUCTION TO FRACTURES AND RESISTIVITY SURVEYS

Basics of Fractures and Resistivity

Fracture Definition

Fractures in tills are typically vertical, although they can be horizontal (Grisak et al., 1976). Vertical fractures have been observed to 21 meters in depth with spacing varying from 2-30 cm, and the length of horizontal fractures varying from 5-600 cm (Grisak et al., 1976). There are locally a large number of oblique fractures in the Lake Border moraine (Chase, 1988). Most fractures are coated with iron and manganese oxides. Iron oxides are the predominant material and is noted to occur in veins up to 6 cm thick. Selenite crystals have also been observed in the upper few meters of the fractures (Grisak et al., 1976). Water that is reducing in nature moving upward through a fractured, oxidized till and depositing iron and manganese oxides in the zone of fluctuating groundwater explains the origin of iron and manganese oxides. Model studies (Sauck & Zabik, 1992) indicate that both resistive and conductive planes result
in higher apparent conductivity in the direction of the plane.

Origin of Fractures in Glacial Till

Horizontal fractures can result from releases of stress due to glacial unloading. Vertical fractures can be caused by regional extension of the earth's crust due to crustal rebound after glacial unloading, by conjugate shearing due to overriding ice movement, or by tension fracturing as a result of primary stress release following removal of glacial ice. The strain patterns that ultimately became fractured upon stress release can also come from glacial loading and from ice shear over existing till (Chase, 1988). Evidence exists that tension cracks in bedrock can lead to fracture formation in the overlying till (Grisak et al., 1976). Once fractures begin, further development is added by volume changes in the till due to desiccation or geochemical processes such as ion exchange or osmosis during periods of groundwater circulation.

Resistivity Surveys

Resistivity surveys are traditionally used to determine the apparent resistivity of soils or rocks at different depths in the earth or at the same depth but at a
sequence of different lateral locations. Resistivity surveys in this study were used to (a) determine the apparent resistivities of unconsolidated materials at different depths and (b) find any variations in apparent resistivities with respect to the azimuth of the readings.

Resistivity measurements are based on Ohm's Law, which states that if a current is applied to the ends of a medium, the voltage drop across the medium will be proportional to the resistive properties of the medium. Stated mathematically, Ohm's Law in one-dimension is

\[ R = \frac{V}{I} \quad \text{(equation 1)} \]

where

- \( R \) = the resistance in ohms,
- \( V \) = the voltage in volts,
- \( I \) = the current in amperes.

Laboratory experiments have shown that for a particular three-dimensional cylindrical medium,

\[ R = \frac{\rho L}{A}, \quad \text{(equation 2)} \]

where

- \( \rho \) = the resistivity as measured in ohm-meters,
- \( L \) = the length of the cylinder in meters,
- \( A \) = the cross sectional area in square meters (Figure 2).
In (a) a voltage difference across the ends of a resistance \( R \) will cause a current \( I \) to flow. In (b), the resistance of the cylinder is directly proportional to its length and to the electrical resistivity of the cylinder material, and is inversely proportional to the cross sectional area of the cylinder. (from Mooney, 1980).

Figure 2. Relationship Between Voltage, Current, and Resistance.
Where resistance is a property of the geometry of the configuration, the resistivity is a bulk property of the medium. Fleming (1986) states that resistivity is the ease or difficulty with which a current passes through a medium. Resistivity values as listed in Keller and Frischknecht (1966) for some common glacial materials are as follows: alluvium and sands, 10 to 800 ohm-meters; clays, 1 to 100 ohm-meters; and unconsolidated wet clays, 20 ohm-meters. The resistivity of the material is highly dependent on the degree of saturation.

Field Measurements

Potential electrodes are placed in a line and between current electrodes to conduct field measurements of resistivity. The potential difference in voltage when a known current is transmitted allows the calculation of the resistivity (Figure 3). Combining equations 1 and 2:

$$\rho = \frac{KV}{I},$$  \hspace{1cm} (equation 3)

where $K$ is a geometric factor depending on the particular resistivity array used. Equation 3 is valid only when the earth is homogeneous. In practice, we use $\rho_a$ (since the earth is rarely considered homogeneous) to define the apparent resistivity. The apparent resistivity may be larger, smaller, or, rarely, equal to the true resistivity (Keller & Frischknecht, 1966).
Figure 3. Electrode Configuration for the Wenner Array.
In this study, the Wenner array was used for azimuthal surveys because of its simple geometry (Taylor, 1982), and Schlumberger arrays (electrical soundings) were used for depth penetration due to existing interpretative programs and relative ease of manipulating the array. The geometric factor for a Wenner array is \(2(\pi)a\), where \(a\) is the "a" spacing (Keller & Frischknect, 1966). The apparent resistivity using a Wenner array is

\[
\rho_a = 2(\pi)aV/I. \quad \text{(equation 4)}
\]

The "a" spacing is a constant for a Wenner array. In this study, the "a" spacing was typically 10, 20, 30, or 40 feet. The spacings were in increments of 10 feet to facilitate calculation of the apparent resistivity and to adjust to the available space at the site due to obstacles. Smaller "a" spacings of 10 and 20 feet were routinely used; however, larger spacings of 30 or 40 feet were often too large to use, except in fields.

The geometric factor for a Schlumberger array (Zhody et al., 1974) is

\[
\pi MN((L/MN)^2-1/4), \quad \text{(equation 5)}
\]

where

- \(MN\) = the distance between the potential electrodes,
- \(L\) = the distance from the center of the array to the current electrode,
such that the distance \( L \) is greater than 5 times the distance \( MN \). Values for \( MN \) ranged from 0.3 meters to 10 meters for larger spreads. The distance from the center of the array to the current electrodes ranged from a low of 1 meter to a high of 46.4 or 215 meters, depending on the available space.

**Azimuthal Resistivity Theory**

Keller and Frischknect (1966) showed that in layered dipping beds, the apparent resistivity measured parallel to the strike of the beds is actually the transverse true resistivity. This is known as the paradox of anisotropy and is due to the fact that while the density of the current controls resistivities, the total measurable current (\( I \)) is used when computing apparent resistivities.

For a set of parallel joints with a frequency great enough to render the medium essentially homogeneous, Taylor (1982, 1984) showed that apparent resistivity is a function of \( \Theta \), the angle between the joint strike and the azimuth of the line array (Figure 4). The orientation of the corresponding resistivity ellipse parallels the major joint orientation. It is generally assumed fractures are saturated; however, in unsaturated material, the current density will be greatest in the medium, therefore also
Figure 4. Relationship Between Joint Strike and Azimuth of Array (from Taylor and Fleming, 1988).
constraining the ellipse to parallel the fractures (Fleming, 1986). For two joint sets, if the "a" spacing is less than the mean joint length, the ellipse will have one or more peaks coinciding with the fracture orientations. In the case where the "a" spacing is greater than the mean joint length, the ellipse will be oriented in a direction coincident with the direction of greatest connectivity (Taylor & Fleming, 1988).

Experiments (Sauck and Zabik, 1992) have shown that the paradox of anisotropy does not exist for "a" spacings that are less than approximately 5 times the thickness of any overburden overlying fractured medium. The overburden allows lateral dispersion of the electrical current, such that the current focussing of the underlying fractured medium is a minor effect, and the paradox of anisotropy does not enter as a significant factor. As the "a" spacing increases or the overburden decreases to negligible thickness, more of the current becomes focussed in the plane of the strike and the maximum apparent resistivity is parallel to the fracture's strike; therefore, the paradox of anisotropy dominates.

**Electrical Soundings**

The principles establishing electrical soundings are the same as the principles for azimuthal surveys. Elec-
trical soundings are used to explore variations in subsurface geology at depth. Schlumberger arrays are commonly preferred for depth soundings to minimize the effect of shallow lateral resistivity variations. Schlumberger arrays are also more convenient than Wenner arrays since the potential inner electrodes are not moved for each reading (Telford, Geldart, Sheriff, & Keys, 1976).

Schlumberger arrays were used for 4 sites. The Bison 2390 resistivity equipment was used for the soundings as well as for the azimuthal studies. Spacings for the potential and current electrodes were established by using preselected logarithmic interval values. The logarithmic values have the following advantages: field data can be compared to precalculated theoretical curves, different curves can easily be transposed on one another, logarithmic coordinates enhances the effects of low resistivity values and they enhance the variations in thickness of shallow layers (Zhody, Eaton, & Mabey, 1974).

Schlumberger array soundings must expand laterally in a line for several hundred feet. Due to cliffs, roads, houses, streams, and human activity, it was possible to conduct Schlumberger array soundings at only four sites.
CHAPTER III
RESISTIVITY METHODS

Forty-four resistivity surveys at 10 sites in southwestern Michigan were conducted during the summers of 1987, 1988, and 1991. Forty azimuthal surveys and four vertical soundings were done in clay tills and dune sand. A Bison 2390 transmitter and receiver were used to conduct all surveys. The advantage of using a Bison 2390 is time synchronization between the transmitter and receiver, as well as the "stacking" of multiple cycles, compensates for natural earth currents, spurious potentials, electromagnetic couplings from the current cables, and induced polarizations in the earth.

Four electrodes were connected to the transmitter and receiver. The potential electrodes were 5-foot steel rods connected to the receiver with 40 feet of wire. The current electrodes were aluminum frames holding approximately 300 feet of cable with an electrode spike on the bottom. Additional cable spools were added for Schlumberger spreads larger than 300 feet.

At each site, initial readings were taken with the amperage set at 20 milliamps and the frequency switch set at 1 Hz. The potential difference, or voltage, as read
on the receiver, was automatically updated every 10 seconds for a 10-cycle average. Readings were recorded when the potential voltage, as read on the receiver, appeared to deviate from preceding readings by less than an arbitrarily chosen 5 percent. If readings deviated by more than 5 percent, an average of three readings were recorded. All readings were recorded or noted after the instrument cycled through the appropriate number of cycles. If readings were consistently within 5 percent with little or no fluctuation, the frequency was changed to 2 and the unit was re-synchronized. At a frequency of 2, the potential voltage was updated every 5 seconds, and the work proceeded quicker.

The current for the current electrodes was held constant (generally at 20 milliamps) for azimuthal surveys but increased or decreased for the soundings to maintain potential voltage readings within an optimal range.

Azimuthal Resistivity Surveys

One azimuthal survey was conducted in dune sand and 38 in clay till. Azimuthal resistivity surveys consist of rotating, at 10° increments, a Wenner array with a fixed "a" spacing around a central point. A Wenner array was used because of its simple geometry (Taylor,
Azimuthal resistivity surveys have been successfully used to determine the porosity of fractured bedrock (Fleming, 1986), the orientation of joints (Leonard-Mayer, 1984) and joint orientation and porosity (Taylor, 1984).

The initial surveys on May 12, 1987, were started with the first array oriented at an azimuth of 100°, and subsequent surveys were begun by taking a reading at 0° and rotating the array clockwise. Initial surveys were rotated 10° by using a transit or Brunton compass to determine 10°; however, it was more expedient to calculate 10° increments by measuring out the legs of an isosceles triangle which would have acute angles of 10° for an appropriate "a" spacing (Figure 5). For all surveys conducted on and after May 30, 1987, the triangle technique was used to establish 10° increments.

An azimuth of 0° was established with a Brunton compass, and 10° increments were established by measurement. Flags were posted at azimuths from 0-180° at 10° spacings. Flags from 190-350° were established by backsighting through the center point to the corresponding azimuth.

Fiberglass tapes were connected to the center point and stretched out in a line from 0-180°. Potential
Figure 5. Calculation of 10° Increment Using Trigonometric Methods.
electrodes and current electrodes were placed next to the tape according to the "a" spacing in use.

Initially, readings were taken at all 36 azimuths; however, after the first azimuthal resistivity survey it became apparent that the readings at 10° was essentially the same as the reading at 190° and data were only collected from half of the circle.

Figure 6 is an azimuthal resistivity survey conducted over the entire range of 360°. In contrast to the asymmetrical shape of the curve in Figure 6, the symmetry of the other azimuthal resistivity surveys is due to the fact that the survey was only conducted over a range of 180°. It is also apparent from Figure 6 that, although perfect symmetry does not exist, with an accuracy of 2 percent and a precision of 1 percent, as stated by the manufacturer, the Bison 2390 is still able to record maximum and minimum values.

Once all electrodes were in place, a reading was taken. After the reading, the tapes and electrodes were rotated 10° clockwise. The tapes and electrodes were rotated until a reading was taken at 180°. If the reading at 0° was within 5 percent of the reading at 180°, the survey was complete and a new "a" spacing was used.
Date: May 12, 1987
Soil: sand
Depth to water: unknown
Distance between circles: 2.5 ohm-m
Resistivity range: 32.4-46.4
Mean value: 39.4 ohm-m
Standard deviation: 3.9

Figure 6. Azimuthal Resistivity Survey Rotated Throughout a Full Circle at 10° Increments With an "a" Spacing of 20 Feet.
Electrical Soundings

Schlumberger arrays were used for soundings in clay tills. Spacings were done on a logarithmic basis to better compare field data with theoretical curves, suppress the affect of lateral variations of thickness with depth and enhance the variations of thickness of shallow layers, and enhance variations in low resistivity values. Schlumberger sounding curves were interpreted on a computer program developed by Zhody (Zhody et al., 1974).
CHAPTER IV

RESULTS OF FIELD INVESTIGATION

Azimuthal surveys were conducted at 10 sites in two counties along the western edge of Michigan during the summers of 1987, 1988, and 1991 (see Site Map in Appendix A). Seven sites—Brandl, Swanson, McGrew, Clark, Access Point, "C," and Briarhills—were chosen due to their proximity to areas of fractures known from prior field investigations of fractured till (Chase, 1988); an exception was the Briarhills site, where fractures were located independent of other work. Extensive research was done at two sites, Field and Brandl, because of the availability of large areas of land. Two of these sites are on the beach; "C" is near fractures and North Beach is near homogeneous sands. The exact location of each azimuthal survey is detailed in the appendix.

One survey was conducted at each of the "C" and North Beach sites, whereas multiple surveys were conducted at the remaining eight sites. Attempts were made to conduct depth soundings using Schlumberger arrays; but, because of roads, vegetation, or buildings it was not always possible to find enough space to conduct a survey which would penetrate to an appropriate depth. Fractures
were observed and documented at all but the Cenediak, Field, and North Beach sites.

The results of the field measurements were plotted on circular diagrams with the maximum value at the edge of the circle and the minimum value at the center. Radial increments were calculated to preserve the minimum and maximum values at the center and edge, respectively.

North Beach Site

One azimuthal survey was conducted at North Beach in South Haven. It was not possible to conduct a Schlumberger array due to the usual ongoing summertime activities at the beach. The North Beach site was chosen to determine if it was possible to obtain consistent resistivity values in apparently homogeneous sand.

Fracture Analysis

There was no clay nearby for fracture observation.

Resistivity Surveys

An azimuthal survey with an "a" spacing of 16 feet was conducted. The results are shown in Figure 7. The apparent resistivity ranges from 169.3-173.6 ohm-meters. Since the Bison 2390 has an accuracy of 2 percent, the actual minimum value could be 165.9-172.7 and the upper
Date: 5/19/88
Soil: beach sand
Depth to water: 18 inches
Distances between circles: 1.0 ohm-m
Resistivity range: 169.2-173.6
Mean value: 171.8 ohm-m
Standard deviation: 1.1 ohm-m

Figure 7. Azimuthal Resistivity Survey at the North Beach Location With an "a" Spacing of 16 Feet.
value could range from 170.1-177.1. With the above range of values, the azimuthal diagram could be essentially a circle. The irregular shape of Figure 7 is due to the small standard deviation of 1.1 ohm-meters. If the data were presented on an arithmetic scale, the figure would appear as a circle.

Field Site

Six azimuthal surveys and one vertical sounding were conducted in the summer of 1988.

Fracture Analysis

A fracture analysis was not conducted at the field site due to a lack of readily exposed till fractures. Although the field site was located next to the bluffs at Lake Michigan, the exposed till and sand, due to mass movement, sloped down to the beach without affording the opportunity to observe till fractures. Fractures in the sloping till are numerous, but were observed to be generally desiccation cracks due to weathering processes.

Resistivity Surveys

Six azimuthal surveys and one vertical sounding were conducted in the summer of 1988 at the field site. The vertical sounding (Figure 8) indicates the subsurface
GLENN FLD1 (INTERPRETATION)

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Figure 8. Vertical Electrical Sounding at the Field Location.
geology consists of approximately 0.3 to 0.6 meters of topsoil, up to 9 meters of clays and sandy deposits, with bedrock located at a depth of greater than 45 meters.

Of the 6 surveys, F2 and F3 (Figures 9-12) were conducted near the edge of the cliff in May and June, and F4 (Figures 13-14) was conducted further away from the cliff in July. F2 and F3 show increasing resistivity with depth, and F4 shows resistivity decreases. The high resistivity values for an "a" spacing of 10 feet at F4 may be due to extremely dry surface conditions.

The lack of correspondence between the diagram for the 10-foot and 20-foot "a" spacings can be largely explained by the "overburden effect" (Sauck & Zabik, 1992). The soil thickness is appreciable relative to the 10-foot spacing, and hence the major axis of the ellipse is perpendicular to the joints. With increasing "a" spacing, the soil thickness becomes negligible and the paradox of anisotropy (current focussing) comes into play and the diagram shows an apparent rotation of 90°.

The range of F4 is significantly greater than the instrumental uncertainty and the patterns are similar enough to suggest there is some correspondence at the two different depths being investigated. The shallow survey indicates an orientation of 150° for \( \rho_a \) max with a minimum apparent \( \rho_a \) value perpendicular to the maximum value.
Date: 5/29/88
Soil: Sand over clay
Depth to water: unknown
Distances between circles: 0.5 ohm-m
Resistivity range: 27.5-30.2
Mean value: 28.8 ohm-m
Standard deviation: 0.7 ohm-m

Figure 9. Azimuthal Resistivity Survey at the Field Location; Site F2 With An "a" Spacing Of 10 Feet.
Date: 5/29/88
Soil: Sand over clay
Depth to water: unknown
Distances between circles: 0.6 ohm-m
Resistivity range: 37.7-41.1 ohm-m
Mean value: 38.6 ohm-m
Standard deviation: 1.0 ohm-m

Figure 10. Azimuthal Resistivity Survey at the Field Location; Site F2 With an "a" Spacing of 20 Feet.
Date: 6/7/88
Soil: Sand over clay
Depth to water: 2-3 feet
Distances between circles: 0.5 ohm-m
Resistivity range: 24.6-27.2 ohm-m
Mean value: 25.5 ohm-m
Standard deviation: 0.8 ohm-m

Figure 11. Azimuthal Resistivity Survey at the Field Location; Site F3 With an "a" Spacing of 10 Feet.
Date: 7/1/88  
Soil: Sand over clay  
Depth to water: 2-3 feet  
Distances between circles: 0.3 ohm-m  
Resistivity range: 34.5-36.2 ohm-m  
Mean value: 35.2 ohm-m  
Standard deviation: 0.5 ohm-m  

Figure 12. Azimuthal Resistivity Survey at the Field Location; Site F3 With an "a" Spacing of 20 Feet.
Date: 7/17/88
Soil: Sand over clay
Depth to water: 2-3 feet
Distances between circles: 25 ohm-m
Resistivity range: 152-296 ohm-m
Mean value: 221 ohm-m
Standard deviation: 53.2 ohm-m

Figure 13. Azimuthal Resistivity Survey at the Field Location; Site F4 With an "a" Spacing of 10 Feet.
Date: 7/11/88
Soil: Sand over clay
Depth to water: 2-3 feet
Distances between circles: 5.5 ohm-m
Resistivity range: 84.3-116.7 ohm-m
Mean value: 102.0 ohm-m
Standard deviation: 9.8 ohm-m

Figure 14. Azimuthal Resistivity Survey at the Field Location; Site F4 With an "a" Spacing of 20 Feet.
(60°). The deeper reading has a maximum value at 120° azimuth with the minimum value at 30° perpendicular to the maximum.

Briarhills Site

The Briarhills Site, in South Haven Township, was a construction site located in a ground moraine of the Lake Border Moraine (Giroux, et al., 1964). The drift in the area is generally greater than 60 meters thick as shown by a Schlumberger array sounding (see resistivity survey in Figure 15). Two azimuthal surveys, a Schlumberger sounding, and a fracture analysis were conducted at the Briarhills Site in the summer of 1988.

Fracture Analysis

The fracture analysis consisted of 140 measurements using a plexiglass plate and a Brunton compass. The measurements were made in trenches excavated for foundations for an apartment complex. To avoid biasing the survey, 54 measurements were made in east-west trenches and 89 measurements were made in north-south trenches. Plots of the poles of the planes measured in east-west trenches and corresponding plots of measurements in north-south trenches show the inherent bias (Figures 16 and 17). A contoured plot of all data points
Figure 15. Vertical Electrical Sounding at the Briarhills Location.

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Figure 16. Plot of the Poles of Fracture Orientations in an East-West Trench at the Briarhills Location.
Figure 17. Plot of the Poles of Fracture Orientations in a North-South Trench at the Briarhills Location.
indicates arrays of vertical fractures, a significant number of horizontal fractures, and a few scattered data points. Examination of the tills show predominant vertical fractures coated with calcite or filled with tree roots.

Although horizontal fractures are plentiful, they are small and terminate in vertical fractures. While the lengths of vertical fractures were observed to exceed 8 feet, the horizontal fractures were usually less than 1 foot in length. The apertures of the vertical fractures often exceeded 1 mm and averaged greater than 0.5 mm. The apertures of the horizontal fractures were rarely larger than 1 mm and averaged less than 0.5 mm.

Resistivity Surveys

Figure 15 is an electrical sounding conducted at the Briarhills site using a Schlumberger array. The interpretation of the electrical sounding using Zhody's computer model indicates the site contains 0.3-0.6 meters of topsoil overlaying thick deposits of till. Survey B2 (Figure 19), conducted prior to any excavation, shows a strong preferred orientation at an azimuth of 25°. The coefficient of anisotropy (2.32) is the second highest value found, indicating a highly fractured till or possibly a cultural effect (buried pipe or wire). The con-
Figure 18. Plot of the Poles of All Fracture Orientations in Trenches at the Briarhills Location.
Date: 7/10/88
Soil: clay
Depth to water: unknown
Distances between circles: 6.0 ohm-m
Resistivity range: 26.7-61.9 ohm-m
Mean value: 40.2 ohm-m
Standard deviation: 11.3 ohm-m

Figure 19. Azimuthal Resistivity Survey at the Briarhills Location; Site B2 With an "a" Spacing of 10 Feet.
toured plot of poles to the fractures (Figure 17) indicates two major vertical fracture planes, at orientations of $13^\circ$ and $44^\circ$. The intersection of these two fracture sets would allow current or water to move in a horizontal direction at $15^\circ$. If fractures are shorter than the electrode spacing, current flow would be a function of the orientation of the angle made by the intersection of the fractures (Fleming, 1986). A rose diagram (Figure 20) of the fractures also indicates a potential orientation at $25^\circ$, which would be the preferred orientation of current or water moving through the till.

Survey B3 (Figure 21) was conducted 30 feet south of Site B2 after a rectangular foundation trench (60 X 200 feet) 4 feet wide was excavated to a depth of 2-4 feet, around the survey sites. The rectangle's long diagram is north-south. Survey B3 was conducted to within 10 feet of the trench walls. The azimuthal plot of the apparent resistivities at B3 (Figure 21) shows a strong preferred orientation in the east-west direction. It is possible that survey B3 sits on top of a fracture network paralleling the east-west direction, which was enhanced by the excavation, although Figure 20 does not support this view. Excavation could have opened up fractures close to the edge of the survey, thereby biasing the apparent resistivity values.
One circle equals 2 fractures

Figure 20. Rose Diagram of the Fractures at the Briarhills Location.
Date: 7/17/88
Soil: clay
Depth to water: unknown
Distances between circles: 2.0 ohm-m
Resistivity range: 34.6-46.6 ohm-m
Mean value: 41.2 ohm-m
Standard deviation: 4.4 ohm-m

Figure 21. Azimuthal Resistivity Survey at the Briarhills Location; Site B3 With an "a" Spacing of 10 Feet.
"C" Site

"C" Site is located on the beach adjacent to a fracture analysis that was performed on the nearby clay till. "C" site is named for a nearby fracture analysis site (Chase, 1988), which is also called "C". One azimuthal survey was conducted at the "C" site in the summer of 1988.

Fracture Analysis

A fracture analysis on the exposed clay was performed earlier (Chase, 1988). Chase's data were compared to the azimuthal survey result conducted on the nearby beach and are shown in the diagram in Figure 22.

While most of the fractures occur over a broad range of compass points, several large fractures were noted that occur perpendicular to the face of the exposure and are oriented in an east-west direction. There were numerous oblique fractures and a lack of noticeable fractures occurring at orientations between 120-150°.

Resistivity Surveys

Since the fractures were in the clay exposed next to the beach, it was not necessary to conduct a depth sounding. The profile as determined from digging consists of
Figure 22. Stereographic Plot of the Fractures at the "C" Location. Data are from Chase (1988).
2 feet of sandy beach deposits overlying the clay till. The clay till at this site is covered with a thick overburden of sand, therefore the survey was conducted adjacent to the till on the beach.

An azimuthal survey was conducted next to the fracture analysis site on May 28, 1988 (Figure 23). An "a" spacing of 10 feet was used because of the proximity of Lake Michigan. The resistivity values ranged from a low of 76.1 ohm-meters to a high of 81.8 ohm-meters. The average values was 78.7 ohm-meters with a standard deviation of 1.5.

The plot of the azimuthal survey in Figure 23 shows two prominent lobes; however, because the Bison 2390 has a precision of 1 percent, these lobes could vary by approximately .8 ohm-meters making the large lobes significantly less pronounced. At this site, the soil depth of 2 feet is appreciable relative to the "a" spacing. Hence, the ellipse may not indicate fracture orientation.

Clark Site

The Clark Site is located near a small creek which cuts through the clay till. Due to the uneven topography, it was not possible to conduct a depth sounding. In addition, the azimuthal survey, during the summer of 1987, was conducted on a bench 20-30 feet above the creek.
Date: 5/28/88
Soil: beach sand
Depth to water: 15 inches
Distances between circles: 1.0 ohm-m
Resistivity range: 76.1-81.8 ohm-m
Mean value: 78.7 ohm-m
Standard deviation: 1.5 ohm-m

Figure 23. Azimuthal Resistivity Survey at the "C" Location With an "a" Spacing of 10 Feet.
bed where the fracture orientations were recorded and the entire cross section as viewed from the creek is clay till.

**Fracture Analysis**

A fracture analysis (Figure 24) was available (Chase, 1988) and was used for comparison purposes. The fracture analysis indicates many fractures exist at azimuths of 85°, 110°, and 135°. The average orientation is 110°.

**Resistivity Surveys**

Three azimuthal resistivity surveys were conducted in the middle of the turnaround at the end of a dead end road. Two surveys using an "a" spacing of 10 and 20 feet were conducted in June 1987 (Figures 25-26). A third survey with an "a" spacing of 20 feet was conducted in October 1990 (Figure 27).

The range of the apparent resistivities in all surveys is great enough to be significantly larger than the inherent scatter of the instrument. The orientation of the apparent resistivity ellipses from the three surveys varies from 90° to NS to 150°. Each survey has a distinct orientation with coefficients of anisotropies ranging from 1.17 to 1.61. Overhead utility lines were
Figure 24. Rose Diagram of the Fractures at the Clark Location. Data are from Chase (1988).
Date: 6/5/87
Soil: sand over clay
Depth to water: unknown
Distances between circles: 8.0 ohm-m
Resistivity range: 278.3-325.7 ohm-m
Mean value: 300.5 ohm-m
Standard deviation: 14.5 ohm-m

Figure 25. Azimuthal Resistivity Survey at the Clark Location With an "a" Spacing of 10 Feet.
Date: 6/5/87
Soil: sand over clay
Depth to water: unknown
Distances between circles: 15.5 ohm-m
Resistivity range: 147.1-237.5 ohm-m
Mean value: 181.3 ohm-m
Standard deviation: 30.6 ohm-m

Figure 26. Azimuthal Resistivity Survey at the Clark Location With an "a" Spacing of 20 Feet, 1987.
Date: 10/20/90
Soil: sand over clay
Depth to water: unknown
Distances between circles: 11.0 ohm-m
Resistivity range: 125.2-189.2 ohm-m
Mean value: 148.1 ohm-m
Standard deviation: 17.8 ohm

Figure 27. Azimuthal Resistivity Survey at the Clark Location With an "a" Spacing of 20 Feet.
noted at the site and there may be additional underground utilities or trenches which would run in a north-south direction.

**Access Point**

The access point for Lake Michigan in the Glenn area provided an ideal site to conduct surveys. Nine azimuthal surveys were conducted in the summers of 1987-88. A fracture analysis completed by Chase (1988) was used for reference.

**Fracture Analysis**

A fracture analysis (Chase, 1988) was converted from the stereographic projection to a rose diagram (Figure 28) to better observe the orientation of the fractures. Fractures were measured in the clay bluffs and surveys were conducted on the beach (A), on top of the bluff (A1), and approximately 150 feet from the bluff (A2). The original fracture analysis measured the fractures' aperture and orientation. The majority of the fractures are oriented in an east-west direction (Figure 28), and are not differentiated with regard to aperture on the rose diagram.
Figure 28. Rose Diagram of Fractures at the "A" Location. Data are from Chase (1988).

One circle equals 2 fractures
Resistivity Surveys

Seven surveys were run at A2 and one each on the beach and at A1. The initial survey at A2 was run 360° to verify that readings opposite each other were equivalent (Figure 6). Subsequent surveys were conducted from 0° to 180°. Two sets of surveys were conducted with "a" spacings of 10, 20, and 30 feet at the A2 location to verify that the results are reproducible.

The resistivity survey conducted on the beach (Figure 29) shows a general agreement with the fracture analysis. The minimum value occurs at an orientation where no fractures exist, although the maximum value for the azimuthal survey appears off by 20° in a clockwise rotation. The precision of the Bison does not allow for the range of discrepancies.

An azimuthal survey (Figure 30) was conducted on top of the bluff where the fracture analysis was conducted. Resistivities ranged from 11.6-33.8; too large a range to be due to the 1 percent fluctuations in the Bison 2390. The maximum and minimum values appear to coincide nicely with the rose diagram.

In May 1987, six surveys were conducted at "a" spacings of 10, 20, and 30 feet at location A2. Three surveys were conducted in the morning and three in the
Date: 6/5/88
Soil: sand over clay
Depth to water: unknown
Distances between circles: 3.8 ohm-m
Resistivity range: 77.5-99.2 ohm-m
Mean value: 89.7 ohm-m
Standard deviation: 6.8 ohm

Figure 29. Azimuthal Resistivity Survey at the Access Location; on the Beach at Site "A" With an "a" Spacing of 10 Feet.
Date: 5/12/87
Soil: sand over clay
Depth to water: 10 inches
Distances between circles: 3.8 ohm-m
Resistivity range: 11.6-33.8 ohm-m
Mean value: 25.7 ohm-m
Standard deviation: 6.9 ohm

Figure 30. Azimuthal Resistivity Survey at the Access Location; at Site Al With an "a" Spacing of 20 Feet.
afternoon. The plots of the surveys are shown in Figures 31 to 36.

In general, the orientation of the plot of the apparent resistivities remained constant between the morning and afternoon. The coefficient of anisotropy remained essentially constant for the surveys with "a" spacings of 10 and 30 feet; however, it increased for the 20-foot "a" spacings from 1.32 in the morning to 1.48 in the afternoon. While the average apparent resistivity decreased for all surveys, the 10- and 30-foot spacings showed decreases of approximately 2 percent, while the 20-foot spacings indicated a decrease of 11 percent.

Swanson Site

The Swanson Site is located on top of the bluffs adjacent to a fracture analysis site (Chase, 1988). The site is in an open area where a house had been. The house was demolished and the location and nature of any subsurface structure is unknown. A fracture analysis and one azimuthal survey were conducted the summer of 1987.

Fracture Analysis

The fracture analysis (Figure 37) indicated a lack of predominant fractures in a north-south direction. Two sets of fractures are oriented at 40°, 90°, and 110°.
Date: 5/27/87  
Soil: sand over clay  
Depth to water: 10 inches  
Distances between circles: 1.6 ohm-m  
Resistivity range: 37.1-47.4 ohm-m  
Mean value: 41.5 ohm-m  
Standard deviation: 3.3 ohm-m

Figure 31. Azimuthal Resistivity Survey at the Access Location; at Site A2 With an "a" Spacing of 10 Feet (a.m.).
Date: 5/27/87
Soil: sand over clay
Depth to water: 10 inches
Distances between circles: 1.9 ohm-m
Resistivity range: 34.2-45.3 ohm-m
Mean value: 40.7 ohm-m
Standard deviation: 3.5 ohm-m

Figure 32. Azimuthal Resistivity Survey at the Access Location; at Site A2 With an "a" Spacing of 20 Feet (a.m.).
Date: 5/27/87
Soil: sand over clay
Depth to water: 10 inches
Distances between circles: 2.4 ohm-m
Resistivity range: 32.5-46.3 ohm-m
Mean value: 39.1 ohm-m
Standard deviation: 4.4 ohm-m

Figure 33. Azimuthal Resistivity Survey at the Access Location; at Site A2 With an "a" Spacing of 30 Feet (a.m.).
Date: 5/27/87
Soil: sand over clay
Depth to water: 10 inches
Distances between circles: 2.0 ohm-m
Resistivity range: 35.9–46.8 ohm-m
Mean value: 40.7 ohm-m
Standard deviation: 3.6 ohm-m

Figure 34. Azimuthal Resistivity Survey at the Access Location; at Site A2 With an "a" Spacing of 10 Feet (p.m.).
Date: 5/27/87
Soil: sand over clay
Depth to water: 10 inches
Distances between circles: 2.5 ohm-m
Resistivity range: 29.1-43.1 ohm-m
Mean value: 36.6 ohm-m
Standard deviation: 4.6 ohm-m

Figure 35. Azimuthal Resistivity Survey at the Access Location; at Site A2 With an "a" Spacing of 20 Feet (p.m.).
Date: 5/27/87
Soil: sand over clay
Depth to water: 10 inches
Distances between circles: 2.4 ohm-m
Resistivity range: 32.8-46.3 ohm-m
Mean value: 38.5 ohm-m
Standard deviation: 4.5 ohm-m

Figure 36. Azimuthal Resistivity Survey at the Access Location; at Site A2 With an "a" Spacing of 30 Feet (p.m.)
Figure 37. Rose Diagram of the Fractures at the Swanson Location. Data are from Chase (1988).
Resistivity Surveys

Due to adjacent homes, road, and cliff, it was not possible to conduct a Schlumberger depth sounding at the Swanson site. The results of the azimuthal survey are shown in Figures 38 and 39. Two surveys were conducted with "a" spacings of 10 and 20 feet.

The shallow survey had relatively high apparent resistivities, with a mean value of 221 ohm-meters and a standard deviation of 39. The deeper survey had a more restrictive range of values with a mean value of 82.5 ohm-meters and a standard deviation of 8.5 ohm-meters. Both surveys show a pronounced north-south orientation with minimum values at 90° or 65°.

McGrew Site

The McGrew site is located in the backyard of a residence near the "D" site of fracture analysis (Chase, 1988). It is unknown if there are buried structures at this location. A fracture analysis and one azimuthal survey were conducted in the summer of 1987.

Fracture Analysis

The fracture analysis (Figure 40) indicates a multitude of fractures arranged in no preferred orientation.
Date: 7/17/87
Soil: sand over clay
Depth to water: unknown
Distance between circles: 20 ohm-m
Resistivity range: 160.5-280.8
Mean value: 220.8947 ohm-m
Standard deviation: 39.9

Figure 38. Azimuthal Resistivity Survey at the Swanson Location With an "a" Spacing of 10 Feet.
Date: 7/17/87
Soil: sand over clay
Depth to water: unknown
Distance between circles: 5.5 ohm-m
Resistivity range: 65.7-99.0 ohm-m
Mean value: 82.5 ohm-m
Standard deviation: 8.5

Figure 39. Azimuthal Resistivity Survey at the Swanson Location With an "a" Spacing of 20 Feet.
One circle equals 1 fracture

Figure 40. Rose Diagram of the Fractures at the McGrew Location. Data are from Chase (1988).
Resistivity Surveys

Due to intervening roads and homes, no Schlumberger array depth sounding was conducted. The resulting azimuthal surveys (Figures 41 to 42) are similar to the surveys at the Swanson site in that the shallow survey has a large range, high mean value, and high standard deviation, whereas the deeper survey has a smaller range, lower mean value, and smaller standard deviation. Both the Swanson and McGrew sites indicate strong azimuthal orientations in northerly directions without accompanying fracture orientations.

Brandl Site

The Brandl site was chosen because of its proximity to station F of the fracture research (Chase, 1988). The Brandl site contained a large lawn between two homes. Due to the open area, 12 azimuthal surveys and 1 depth sounding were conducted.

Fracture Analysis

A fracture analysis on the exposed clay till was performed by Chase (1988). His data were used as a comparison for the azimuthal surveys conducted on top of the bluff. The results of his stereoplot were analyzed and

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Date: 7/13/87
Soil: sand
Depth to water: unknown
Distance between circles: 8.5 ohm-m
Resistivity range: 188.7-238.1
Mean value: 211.8 ohm-m
Standard deviation: 11.8

Figure 41. Azimuthal Resistivity Survey at the McGrew Location With an "a" Spacing of 10 Feet.
Date: 7/7/87
Soil: sand
Depth to water: unknown
distance between circles: 3.8 ohm-m
Resistivity range: 83.3-105.3
Mean value: 90.8 ohm-m
Standard deviation: 5.3126

Figure 42. Azimuthal Resistivity Survey at the McGrew Location With an "a" Spacing of 20 Feet.
plotted in a Rose diagram (Figure 43).

The results of the fracture analysis show a strong preferred orientation in a southeast-northwest direction. Of 43 measured fractures, 28 are oriented in a southeast-northwest direction. Approximately 20 percent of the remaining fractures are oriented slightly east of north.

Resistivity Surveys

A Schlumberger array sounding was set up parallel to and approximately 45 meters from the cliff. The results of the survey (Figure 44) indicate the surface layer appears to be from 1.5-2.0 meters thick and overlies a layer of less resistive material. The less resistive material has apparent resistivities ranging from 40-50 ohm-meters to depths of 20 meters.

Twelve azimuthal arrays were conducted at 5 spots during the summers of 1987 and 1988. Survey site F2 is located adjacent to station F; however, the remaining sites are located south of station F in a vacant lot. Survey site R2 is located near the bluff, R3 is roughly 100 feet from the bluff, and R4 and R4a are approximately 150 feet from the bluff. The "a" spacings were 3, 10, 20, and 40 feet. Five surveys each were conducted at the 10- and 20-foot spacings. The mean value of apparent resistivities ranged from a high of 546 ohm-meters for
One circle equals 2 fractures

Figure 43. Rose Diagram of the Fractures at the Brandl Location. Data are from Chase (1988).
Figure 44. Vertical Electrical Sounding at the Brandl Location.
the survey at R4a with an "a" spacing of 3 feet to a low of 62.3 for the survey at R4a using an "a" spacing of 30 feet. The mean value for the apparent resistivity at each spot always decreased as the "a" spacing increased and the corresponding depth of penetration increased. The variations in the apparent resistivities at all locations were greater than that accounted for by the intrinsic error of the Bison 2390.

Many of the individual surveys, such as F2-20 feet, R2-10 feet, R4-20 feet, R4a-3 feet, R4a-10 feet, and R4a-20 feet, show strong preferred orientations in one or more directions (Figures 46, 47, and 52-55). Due to the principle of dispersion in overburden (Sauck and Zabik, 1992, the preferred orientations of the shallow penetration of the azimuthal surveys with "a" spacings of 3 and 10 feet are doubtful.

Although the thickness of the sand layer at the bluff is approximately 0.6 meters, the thickness of the top sand layer at each survey location is unknown; therefore, many of the shallow surveys may suffer from overburden dispersion. Survey F2 (Figure 45) at 10 feet shows the least resistivity in a southeast direction; however, when the "a" spacing increases, this same southeast direction becomes the greatest resistivity due to the paradox of anisotropy.
Date: 8/8/88
Soil: sand over clay
Depth to Water: 16 feet
Distance between circles: 17 ohm-m
Resistivity range: 282.0-380.1
Mean value: 325.9 ohm-m
Standard deviation: 30.7 ohm-m

Figure 45. Azimuthal Resistivity Survey at the Brandl Location at Site F2 With an "a" Spacing of 10 Feet.
Date: 7/31/87
Soil: 2' sand over clay
Depth to water: unknown
Distance between circle: 0.75 ohm-m
Resistivity range: 62.3-66.8
Mean value: 64.4842 ohm-m
Standard deviation: 1.4

Figure 46. Azimuthal Resistivity Survey at the Brandl Location at Site F2 With an "a" Spacing of 20 Feet.
Date: 5/25/88  
Soil: sand over clay  
Depth to water: unknown  
Distance between circles: 1.8 ohm-m  
Resistivity range: 108.1 - 118.1  
Mean value: 113.1 ohm-m  
Standard deviation: 3.4  

Figure 47. Azimuthal Resistivity Survey at the Brandl Location at Site R2 With an "a" Spacing of 10 Feet.
Date: 5/24/88
Soil: sand over clay
Depth to water: unknown
Distance between circles: 1.5 ohm-m
Resistivity range: 72.8-80.9
Mean value: 76.7
Standard deviation: 2.2

Figure 48. Azimuthal Resistivity Survey at the Brandl Location at Site R2 With an "a" Spacing of 20 Feet.
Date: 5/31/88
Soil: sand over clay
Depth to water: unknown
Distance between circles: 3.7 ohm-m
Resistivity range: 113.4-134.7
Mean value: 125.9 ohm-m
Standard deviation: 6.5

Figure 49. Azimuthal Resistivity Survey at the Brandl Location at Site R3 With an "a" Spacing of 10 Feet.
Date: 5/31/88
Soil: sand over clay
Depth to water: unknown
Distance between circles: 1.5 ohm-m
Resistivity range: 77.8-85.6
Mean value: 81.9 ohm-m
Standard deviation: 2.3

Figure 50. Azimuthal Resistivity Survey at the Brandl Location at Site R3 With an "a" Spacing of 20 Feet.
Date: 5/31/88
Soil: sand over clay
Depth to water: unknown
Distance between circles: 3 ohm-m
Resistivity range: 154.0-170.4
Mean value: 162.0 ohm-m
Standard deviation: 5.1

Figure 51. Azimuthal Resistivity Survey at the Brandl Location at Site R4 With an "a" Spacing of 10 Feet.
Date: 5/31/88  
Soil: sand over clay  
Depth to water: unknown  
Distance between circles: 2.1 ohm-m  
Resistivity range: 77.0-89.6  
Mean value: 83.9 ohm-m  
Standard deviation: 4.5

Figure 52. Azimuthal Resistivity Survey at the Brandl Location at Site R4 With an "a" Spacing of 20 Feet.
Date: 8/10/88
Soil: sand over clay
Depth to water: 6'
distance between circles: 52 ohm-m
Resistivity range: 394-699
Mean value: 546 ohm-m
Standard deviation: 97.8

Figure 53. Azimuthal Resistivity Survey at the Brandl Location at Site R4A With an "a" Spacing of 3 Feet.
Date: 8/11/88  
Soil: sand over clay  
Depth to water: 6'  
Distance between circles: 16 ohm-m  
Resistivity range: 293.7-385.0  
Mean value: 333.8 ohm-m  
Standard deviation: 27.3

Figure 54. Azimuthal Resistivity Survey Aa the Brandl Location at Site R4A With an "a" Spacing of 10 Feet.
Date: 8/11/88  
Soil: sand over clay  
Depth to water: 6'  
Resistivity range: 61.9-74.1  
Mean value: 67.5 ohm-m  
Standard deviation: 3.4

Figure 55. Azimuthal Resistivity Survey at the Brandl Location at Site R4A With an "a" Spacing of 20 Feet.
Survey R2 (Figure 47) at 10 feet also shows dispersion with the least resistivities being at the southeast and northern orientations. As the "a" spacing is increased to 20 feet, the overburden dispersion still controls the ellipse, but to a lesser degree.

Survey R3 (Figure 49) shows a preferred orientation in two directions with an "a" spacing of 10 feet. Increasing the "a" spacing to 20 feet modifies the orientation somewhat, but still contains two orientations (Figure 50).

At site R4, the shallow survey with an "a" spacing of 10 feet shows an east-west orientation (Figure 51). Minor variations in the extreme apparent resistivities could be due to variations in the accuracy of the instrument. When the "a" spacing is increased, the orientation becomes north-south in accord with the paradox of anisotropy as overburden thickness becomes small relative to the "a" spacing.

The most extensive work at the Brandl site was done at the R4a site where surveys were conducted with "a" spacings of 3, 10, 20, and 30 feet (Figures 53-56). The shallow survey with an "a" spacing of 3 feet shows dispersion and has the maximum apparent resistivity aligned in a northeast direction. As the "a" spacing increases to 10 and then 20 feet, the maximum apparent resistivity
Date: 8/11/88  
Soil: sand over clay  
Depth to water: 6'  
Distance between circles: 0.6 ohm-m  
Resistivity range: 60.3-63.8  
Mean value: 62.3 ohm-m  
Standard deviation: 0.9

Figure 56. Azimuthal Resistivity Survey at the Brandl Location at Site R4A With an "a" Spacing of 30 Feet.
shifts to a more southeast direction as we move away from overburden domination to true paradox of anisotropy domination. As the survey expands to an "a" spacing of 30 feet, the standard deviation of the apparent resistivity of the azimuthal plot decreased to roughly 1 ohm-meter and the plot becomes highly irregular. With a precision of 1 percent for the Bison 2390, the irregularity of the plot could be strictly a function of the precision of the Bison 2390.

Data for all resistivity work indicates the apparent resistivities and fracture intensity, as measured by the coefficient of anisotropy, decreases with depth. It may be that the more penetrative azimuthal survey is measuring less amounts of fractures due to the interception of another till.

Cenediak Site

The Cenediak Site is located in a large open area in the vicinity of a fracture analysis on a nearby bluff (Chase, 1988). The site is several hundred feet east of the bluff in a field. It is unlikely any septic systems or buried utility lines are located in the area. Three resistivity surveys were conducted during the summer of 1988.
Fracture Analysis

A fracture analysis was not performed adjacent to the Cenediak Site; however, a fracture analysis was performed on the clay till located on the bluff approximately 1500 feet northwest of the site. The fracture analysis (Figure 43) indicates a strong preferred orientation from 130° to 150°. Due to the distance of the fracture analysis from the site, the results of the fracture analysis is not indicative of fracture orientation at the Cenediak site, which was chosen due to the availability of a large open area.

Resistivity Surveys

The following three resistivity surveys were conducted at the Cenediak Site: (1) a Schlumberger depth sounding, (2) an azimuthal survey with an "a" spacing of 20 feet, and (3) an azimuthal survey with an "a" spacing of 40 feet.

The results of the depth sounding (Figure 57) indicate 4 layers: (1) a moderately resistive surface layer, (2) a very resistive layer approximately 4.5 meters thick, (3) less resistive layers down to greater than 50 meters, and (4) a more resistive layer at depth. These layers are interpreted as surface topsoil, sand, fractured unit, and bedrock.
The azimuthal surveys consist of 2 data sets with widely varying values. The 20 foot array (Figure 58) data has the highest resistivity of all arrays due to the presence of the second layer's dry sand. The "a" spacing of 20 feet is not great enough to overcome the current spreading which would occur in the sand layer; therefore the strong preferred orientation in the east-west direction is probably due to the preferential deposition of sand due to glacial action. The 40-foot array (Figure 59) has resistivity values more in line with expected values for clay till. The larger "a" spacing allowed the survey to penetrate the clay and lower the apparent resistivity. However, due to the great thickness of overburden, the maximum direction would be perpendicular to the fractures only if the "a" spacing was large enough to be sampling primarily the clay layer. Neither survey is indicative of the orientation of the fractures at the Brandl site's station F.
**Figure 57. Vertical Electrical Sounding at the Cenediak Location.**

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Date: 7/17/88  
Soil: sand  
Water depth: unknown  
Distance between circles: 160 ohm-m  
Mean value: 2438 ohm-m  
Standard deviation: 238.2029  
Resistivity range: 2061-3023  

Figure 58. Azimuthal Resistivity Survey at the Cenediak Location With an "a" Spacing of 20 Feet.
Date: 8/8/88
Soil: Sand over Clay
Depth to Water: 16 feet
Distance between circles: 17 ohm-m
Resistivity Range: 282.0-380.1
Mean Value: 325.9 ohm-m
Standard Deviation: 30.7 ohm-m

Figure 59. Azimuthal Resistivity Survey at the Cenediak Location With an "a" Spacing of 40 Feet.
CHAPTER V

DISCUSSION AND CONCLUSION

Discussion

The results of the resistivity surveys indicate the following: (a) apparent resistivities generally decrease with depth in clay-rich soils of the Lake Border Moraine, (b) the results are repeatable from day to day, and (c) the relationship between the major axis of the apparent resistivity ellipse and the fracture orientation is highly dependent on soil or overburden thickness relative to electrode spacings. Unfortunately for the conduct of this thesis research, the theory of azimuthal resistivity was incomplete at the time the field work was done. Plus, the design and conduct of the field surveys did not have the benefit of later studies which showed the importance of the soil or overburden in modifying the direction and amplitude of the apparent resistivity ellipses. In retrospect, the thickness of overburden or depth to the anisotropic unit (fractured till) must be known, and lateral variations in the thickness of this soil layer can not be tolerated.

By comparing the maximum and minimum values for the

103
apparent resistivities, it is possible to develop a coefficient of anisotropy which is an indication of the intensity of fracturing (Fleming, 1986). The greatest intensity of fracturing was at the Access site and the least amount at North Beach. As the surveys were moved systematically away from the lakeshore at the Brandl site, the apparent resistivities increased while the coefficient of anisotropy fluctuated between 1.09 and 1.31 (Table 2), possible due to the increasing overburden.

Fracture intensity decreased with depth at eight sites, increased at five sites, and remained constant at one site. The five sites where fractures increased are all adjacent to sites where fracture studies had been conducted earlier (Chase, 1988). Seven sites were adjacent to documented fracture study areas.

Multiple surveys were conducted at 14 sites. At 11 (79%) of the sites, the apparent resistivity decreased with depth. It would be expected that the apparent resistivity would decrease as the azimuthal survey penetrates more conductive clay layers at depth.

Of the three surveys where apparent resistivities increased, two are located near the bluff at the Field site, and one is on top of the bluff at the Access site. The two surveys at the Field site, F2 and F3, clearly
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show resistivity values increase with depth, although the amount of fracturing, as measured by the coefficient of anisotropy, appears to decrease (see Table 2). This would indicate the presence of a more resistive layer of sand. No data were available precisely at this point to confirm or deny the presence of any sand lenses.

When similar surveys were conducted at the A2 site in the morning and afternoon, the afternoon set of surveys show an increase in apparent resistivities. The sudden change in the afternoon values is due to a 10% decrease in the apparent resistivity for the 20-foot "a" spacing.
possible due to installing the current electrodes deeper in the afternoon.

Work at the Access site indicates that the elliptical orientations and relative resistivities are repeatable from day to day; however, the absolute values for the apparent resistivities vary.

Fracture intensity, as defined by the coefficient of anisotropy, decreased with depth at eight sites, increased at five sites, and remained constant at one site. The five sites where fracture intensity increased are all adjacent to sites where fracture studies had been conducted earlier (Chase, 1988). Seven sites were adjacent to documented fracture study areas.

To observe whether the measured fracture orientation was related to the apparent resistivity orientation, comparisons were made between seven fracture studies and the associated azimuthal resistivity surveys. Due to the dispersal effects of surficial sand layers, the shallow surveys with an "a" spacing of 10 feet or less were not used except at the Briarhills and "C" sites, where surface clays were encountered. The Briarhills site was highly fractured near the surface with major fracture orientations of 45°, 75°, and 165°. The intersection of fractures provides an avenue for current or water movement (Fleming, 1986). The orientation of the B-2 survey at 25° corresponds
to a potential fracture intersection pattern. The other azimuthal ellipse, B-3, conducted in the vicinity of B-2 has an elliptical orientation of 90°.

The resistivity ellipse at the "C" location would seem to indicate the presence of two intersecting fracture patterns; however, the associated fracture analysis does not bear this out. This disparity may be due to intervening surficial sands dispersing the current or to numerous oblique fractures.

The Clark site is highly fractured with a well-documented fracture analysis (Chase, 1988); however, the two azimuthal surveys conducted with 20-foot "a" spacings have elliptical orientations at 5° and 30°, while the fracture orientations are at 85°, 110°, and 135°.

The Access Point location was also highly fractured with a very prominent fracture orientation of 100-120°. Roughly half of all observed fractures lie in this orientation. The resistivity ellipse for the survey A-1 conducted on the bluff by the fracture study shows an orientation roughly paralleling the fractures; however, although the other surveys show prominent resistivity ellipses, none of them show alignment with the fracture orientation.

Both the Swanson and McGrew resistivity ellipses show a preferential orientation; however, the fracture study did not indicate a strong corresponding preferred orientation.
The Brandl location shows a strong azimuthal resistivity maximum orientation of 130° to 150°. Twenty of the observed 43 fractures occur at this orientation. Azimuthal surveys at sites F2 and R2 have several lobes indicating multiple fracture sets. The azimuthal surveys at R3 and R4 are oriented at 50° and 20° respectively. Azimuthal surveys at R4a were conducted with "a" spacings of 20 and 30 feet and had orientations of 145° and 80° respectively. However, it should be noted that the orientation of the ellipse for R4a with a 30-foot "a" spacing could be significantly altered due to the instrument fluctuations of 1 percent.

The results of this study were less successful than those of Fleming primarily because of the lack of knowledge of the dispersion effect of the overburden which interfered with shallow surveys. Lack of detailed information concerning the geology also failed to allow the use of surveys tailored to the specific geology at each site. In certain cases, the primary fracture orientation may be controlled by the proximity to the steep cliffs whereas the true orientation is measured by the survey.

Conclusions and Recommendations

Conclusions

Fractured till is well documented in the literature and has been studied at numerous sites in glaciated areas
of the United States and Canada. Fractures greatly alter the till's physical characteristics and may be responsible for increasing the permeability of the fractured unit. Fractures have been observed to a length of 6 meters and a depth of 21 meters. Fractures in the Lake Border moraine are horizontal, vertical, and oblique, with no predominant orientation; however, fractures on several cliffs appear predominantly perpendicular to the face of the cliff.

Of the 38 azimuthal resistivity surveys conducted, the results of 16 of the surveys conducted with "a" spacings of 10 feet or less are susceptible to dispersion of current, which makes the resulting azimuthal plot unreliable for delineating fracture orientations. Six of the remaining surveys were conducted where there were no fractures or no predominant fracture orientations.

Sixteen azimuthal surveys were conducted at a sufficient depth to study fractures at four known fracture locations; however, the alignment of the fractures with the azimuthal resistivities was not good.

Although the resistivity surveys and subsequent plots are repeatable from day to day and the plots appear consistent over a given location, there is not enough consistency between the fracture orientations and the orientation of the azimuthal plot to assign a fracture orientation value to a till unit based on an azimuthal
resistivity survey. If the site geology is well understood, azimuthal surveys may be useful for determining the degree of anisotropy due to fractures and apparent resistivities.

Due to the increase in the use of compacted clay and composite liners, it is doubtful if azimuthal surveys would be of much use in delineating fracture-free natural clay for landfill sites. Since landfill siting procedures are more political than scientific, the value of azimuthal surveys is limited for siting landfills.

Azimuthal surveys would be beneficial for locating sites of highly fractured bedrock for the location of water wells. All things being equal, the site with more fractures would be a better site for a productive water well; however it should be noted that although the water well would be more productive due to fractures, it would also be more prone to contamination.

Although azimuthal resistivity surveys will not precisely delineate fracture orientations, the surveys are still useful for delineating subsurface anisotropy and may be useful for (a) delineating sites for water wells, (b) understanding contaminant flow directions, and (c) delineating abandoned underground mines and natural caverns.

Extensive field work is required prior to conducting azimuthal surveys in order to adjust "a" spacings to the
appropriate level of penetration of the fractured material and to insure that the "a" spacing is sufficiently large to overcome the current spreading due to the overburden. It may be inappropriate to attempt azimuthal resistivities at sites where significant overburden is present.

Additional work that would aid in understanding fractured till include the following: (a) conduct an azimuthal resistivity survey at a site in fractured till or bedrock where the geology is well understood and the environment is contaminated with nonionic organic chemicals; verify that the direction of contaminated flow mirrors the orientation of the ellipse of the azimuthal survey; (b) install soil borings and monitoring wells on a 100 foot grid in an area of fractured till or bedrock; conduct multiple azimuthal resistivity surveys tailored to the specific geologic conditions to verify that azimuthal surveys can be used to characterize fractured units; (c) conduct laboratory experiments using sand tanks to further characterize the relationship between the overburden and the underlying fractured unit.
Appendix A

Site Location Maps
Appendix B

Locations of Field Sites
Locations of Field Sites

**Allegan County**

**Access Location** (3 sites). Section 31 of Ganges Township. Due west of Glenn, on top of the bluff.

"A" - In the middle of the beach, 15 feet from the cliff, 40 feet south of the road down to the beach.
A1 - Immediately on the right as 71st Street bends to the left.
A2 - 120 feet south of 71st Street and 60 feet west of Redman Road.

**Brandl Location** (5 sites). Section 30 of Ganges Township. 1540 71st Street. There are two series of sites at the Brandl property: F series and R series.

F series (1 site):
F2 - 80 feet west of the southwest corner of the cottage, 70 feet east of the cliff.

R series (4 sites): The R series begins in the middle of the vacant lot adjacent to F2, south of 1540 71st Street, on a line beginning 20 feet from a large oak tree in the southwest corner of the lot on a bearing north 105 degrees east.
R2 - 22 feet on a bearing north 105 degrees east, 82 feet from the edge of the cliff
R3 - 63 feet on a bearing north 105 degrees east
R4 - 114 feet on a bearing north 105 degrees east
R4a - 100 feet on a bearing north 105 degrees east, 15 feet on a bearing north 15 degrees east.

**Cenediak Location** (1 site). Section 30 of Ganges Township. 1502 71st Street; 625 feet west of 71st Street on Statler Driveway; 60 feet north of Statler Driveway; just before sharp curve to the left.

**Clark Location** (1 site). Section 31 of Ganges Township. At the end of 71st Street turn left, go to the end of the road, through the gate, in the middle of the turnaround.

**Field Location** (3 sites). Section 13 of Casco Township. 1000 feet past 107th Avenue, left on the first dirt trail, in the middle of a large field.
F2 - 82 feet from the edge of the cliff on a bearing north 70 degrees east, 114 feet south of the intersection of the north south trail and the east west trail.
F3 - 65 feet from F2 on a bearing north 75 degrees east.
F4 - 192 feet from the east west trail and 340 feet from the north south trail.

**McGrew Location** (1 site). Section 30 of Ganges Township. First house on the right on Lake Michigan on Evergreen Lane. 18 feet from the road on a bearing north 85 degrees east from the southwest corner of the cottage.

**Swanson Location** (1 site). Section 30 of Ganges Township. 1405 Katherine, west of road 100 feet, 60 feet from the cliff, 32 feet N55W from a lamp post.

**Kalamazoo County**

**Dowty Location** (1 site). Section 15 of Schoolcraft Township, 955 feet west of Portage Road, 325 feet north of VW Avenue.

**Gergely Location** (1 site). Section 16 of Schoolcraft Township, 335 feet north of the center line of W Avenue and 115 feet east of the center of 16th Street.

**Schug Location** (1 site). Section 13 of Prairie Ronde Township, 3600 feet north of the center of VW Avenue and 220 west of the center of 12th Street.

**Sixteenth Street Location** (1 site). Section 21 of Schoolcraft Township, 170 feet east of the center of 16th Street, 80 feet north of the first field drive south (about 0.25 mile) of 4335 16th Street.

**Van Buren County**

**North Beach Location** (1 site). Section 3 of South Haven Township, 250 feet, N65W, from the center of the road in front of house number 22 at North Beach, South Haven.

**Briarhills Location** (2 sites). Section 11 of South Haven Township, southwest corner of South Haven Street and Blue Star Highway.
B2 - 101 feet south of the edge of South Haven Street & 68 feet west of the edge of Blue Star Highway.
B3 - 132 feet south of the edge of South Haven Street & 87 feet west of the edge of Blue Star Highway.
BIBLIOGRAPHY


