DETECTION OF LATE WISCONSINAN GLACIAL DEPOSITS AND LANDFORMS OF NORTH-CENTRAL OHIO, USA USING IMAGE ENHANCEMENT TECHNIQUES ON LANDSAT TM DATA

A Thesis
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* * * * *

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ABSTRACT

The purpose of this study was to delineate the glacial geology of north-central Ohio using image enhancement techniques and feature selection on Landsat thematic mapper (TM) data. Glacial mapping with TM data has not been fully examined. Full comprehension of the glacial geology is vital to understand the environment, economy, and community life of the Great Lakes region. A contrast stretch (histogram equalization) of (5,4,3), (7,4,1), and (7,5,1) false-color composites all provided spectral discrimination of the glacial geology. Drainage patterns were best determined from a contrast stretch (histogram equalization) of TM band 4. Determination of drainage types allowed for discrimination of lake sediments from till. Convolution filters used on band 4 and the false-color composites did not provide additional detail of the glacial geology.

The Quaternary map of north-central Ohio was overlain on enhanced images for comparison of the TM data with the glacial geology. For mapping clayey till, a (7,5,1) false-color composite provided more detail than a (7,4,1) composite. A ratio image of (7, 7/1, 4/5) (red, green, blue, respectively) depicts variations in the bare fields that allows for detection of lake deposits and till. Lake-planed moraine and ground moraine were delineated using the aforementioned ratio image by variations in vegetation. A principal component analysis (PCA) false-color composite of (PCA4, PC A3, PCA2) (red, green, blue, respectively) also portrays the variations that occur in the bare fields on the glacial
till. Manifest on the PC A image was a linear feature that appears to be a previously unmapped beach ridge. The feature is apparent on PC A3, which is dominated by bands 5 and 7. These bands are hydroxyl-bearing mineral detectors and imply a mineralogical continuity along this feature.
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Many individuals from the Ohio Department of Natural Resources (ODNR) Division of Geological Survey have provided assistance. Thomas Berg and Dennis Hull provided many manuscript maps of my study area. Dennis also clarified the confusion surrounding the bedrock stratigraphic nomenclature of northern Ohio. C. Scott Brockman and Richard Pavey provided additional information through maps and
conversations about the glacial and environmental aspects of the area. Jim McDonald graciously answered my many questions regarding the Geographic Information Systems (GIS) data provided by the Survey.

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CHAPTER 1
INTRODUCTION

The purpose of this study was to integrate Landsat Thematic Mapper (TM) data with a digital glacial map to delineate the glacial deposits and landforms in north-central Ohio, USA. The Landsat-5 TM image was acquired on June 11, 1984 and is centered at N 41°45' 00" latitude and W 083°43'00" longitude, just west of Toledo, Ohio. The southeast quarter of the scene was used (Figure 1.1). The original focus of the study was to analyze this quarter scene and to map the various glacial units, delineate shallow bedrock areas, identify potential karst regions, and examine modern coastal processes. The project was modified to delineate the glacial geology of a small area within the quarter scene.

This study is important because glacial mapping with satellite remote sensing has not been fully examined. The literature addressing this issue indicates that most glacial geologists looked only at single bands without the application of any data analysis techniques. Single spectral bands provide only a limited portion of the electromagnetic spectrum and have poorer spatial resolution than aerial photographs. However, features (such as the position of former ice streams) can be identified on satellite imagery that are not apparent on published maps and aerial photography (Punkari, 1993).
Figure 1.1. Location of the June 11, 1984 Landsat TM quarter scene. Ohio counties included in the scene are labeled. The map projection is Geographic (latitude/longitude). (Modified from the United States Geological Survey, Global Land Information System 1:2,000,000 digital line graph, 1995)
Glacial mapping has become a primary focus for the Great Lakes region. The state geological surveys of Ohio, Indiana, Illinois, and Michigan have partnered with the United States Geological Survey (USGS) to produce detailed surficial maps of the Great Lakes region. This union, the Central Great Lakes Geologic Mapping Coalition, sponsored a meeting in February, 1999 where the importance of glacial mapping was emphasized. USGS Director Charles Groat stated that an understanding of the glacial geology is vital to understanding the hydrology, soils, and other environmental facets of the Great Lakes region. Additionally, many aspects of community life are dependent upon the surficial geology, and an understanding of the surface and near-surface processes is needed to understand the Earth-human interaction (Groat, 1999). Interest in the surficial geology extends beyond the state geologic survey groups, as many agencies, community committees, and private companies have an urgent need for better surficial information (Hester, 1999).

Currently, the glacial geology of the entire state has been mapped at the 1:250,000 scale, and only selected areas have been mapped at larger scales. Many geologic applications involving surficial material demand more detail than presently provided. Landsat TM has the potential to further subdivide the established glacial units, detect variations within units, and even detect previously unnoticed materials or features.

Remote Sensing of Glacial Geology

Glacial geologists have extensively used aerial photography to map glacial deposits and landforms, but the use of satellite imagery for the same purpose has been limited. In the infancy of satellite remote sensing, glacial geologists attempted to use TM data for glacial geology-oriented studies. For example, Lineback (1975) concluded that
the small scale, synoptic views provided by satellite imagery would be useful for surficial geology mapping. However, the glacial geologists concluded that the images were of very little use unless the interpreter had a detailed knowledge of the glacial geology of the region, and that aerial photographs provided better information (Lineback, 1975; Elson, 1980). These geologists had a logical basis for their conclusions: the studies in the applicability of satellite imagery for glacial geology employed visual interpretation of single bands only. Elson (1980) and the research he cited looked at single bands with no image enhancement, no use of true- or false-color composites, or any other data analysis techniques. Any single spectral band covers only a limited portion of the electromagnetic spectrum, and has poorer spatial resolution than aerial photographs. The results of early studies curtailed the interest in remote sensing for many glacial geologists (Elson, 1980).

Although the literature is limited, a number of geologists have utilized satellite images to aid in glacial geology studies. Clark (1997) suggested initially looking at single band images because some geologic landforms may be more apparent displayed in monochrome than in color. Day (1995) studied the distribution of drumlins and moraines in Nova Scotia, Canada using TM band 4. Landforms and till were delineated by using a contrast stretch technique and by knowledge of the soil moisture and vegetation type characteristics of these features. This enhanced image exhibited a high degree of correlation with previously published surficial geology maps of the study area. Moore and Gregory (1973) found that time of year controlled the amount and type of glacial information contained in the satellite image. Their temporal study of images of the Northwest Territories in Canada demonstrated that eskers and moraines were enhanced in October images due to the low sun angle. In May images, the residual snow cover
demarcated drumlin fields and esker swarms. Also apparent in May images was new vegetative growth on lacustrine clays. The vegetative differences on glacial deposits became more pronounced in June imagery. Moore and Gregory noted that without the temporal analysis, much of the glacial information would have been lost.

Many studies have not been as successful in discriminating till types and end moraines (Clark, 1997). In fact, end moraines are seldom successfully detected on Landsat TM images (Elson, 1980). Isachsen et al. (1973) evaluated satellite imagery for the detection of end moraines in New York state, but only a few short segments of some moraines were detected. These segments were identified based on land use differences compared to the surrounding ground moraine.

In areas of continental glaciation, end moraines often are composed of the same till material as the surrounding ground moraine. The composition is the same for the landforms, and thus the spectral response is the same. This effect has led to the use of geobotany to distinguish glacial landforms (Punkari, 1982). The morphology of end and ground moraines differ, and the morphology and material of a landform determine the vegetation, soil moisture, soil organic matter content, erosion, and land use. These properties in turn can be used to distinguish glacial landforms (Punkari, 1982). Aber et al. (1993) developed a band ratio false-color composite scheme to effectively display the geobotanical aspects of the land surface. This scheme displayed Landsat Multispectral Scanner (MSS) band 3 as red, MSS 4/2 as green, and MSS 1/2 as blue. The geobotanical method suggested by Punkari (1982) is effective on spring imagery (May and June), when vegetation phenology and soil moisture conditions indicate the subtleties in
material, organic matter content, erosion, and land use (Aber et al., 1993). These characteristics can then be used to determine the glacial landform present.

**General Geologic Setting**

The study area is centered at 41°12'00" N latitude and 82°54'00" W longitude, roughly at the junction of Erie, Huron, Seneca, and Sandusky Counties (Figure 1.2). The northwest corner of the area is located northeast of Fremont at 41°24'45" N latitude and 083°02'14" W longitude (Figure 1.3). The northeast corner is positioned south of Sandusky at 41°22'01" N latitude and 082°43'32" W longitude. The southeasternmost point in the study area is west of Willard at 41°03'07" N latitude and 082°48'37" W longitude. The southwest corner is located east of Tiffin at 41°05'54" N latitude and 083°07'09" W longitude. This region is 18 miles wide and 23 miles long (414 mi²).

Agricultural land use dominates the study area, although there are two prominent urban areas, Bellevue (1990 population 8146, approximate area 4 mi²) and Clyde (1990 population 5776, approximate area 4 mi²) (Figure 1.3). The presence of glacial deposits in the study region is important for the extensive agricultural use of the land. Low relief end moraine and ground moraines dissected by post-glacial fluvial features characterize the area. Also present are raised beach ridges and lake deposits that formed from the different stages of Lake Erie during and following the Wisconsinan glaciation.

The topography of the study area is rolling to flat; the relief is 370 feet with elevations ranging from 600 feet in the north to 970 feet in the south. The Defiance End Moraine (southern portion of the map) crests at 970 feet; the northern boundary of the
Figure 1.2. Location of the June 11, 1984 Landsat TM subset area. Ohio counties included in the study area are labeled. The map projection is Geographic (latitude/longitude). (Modified from the United States Geological Survey, Global Land Information System 1:2,000,000 digital line graph, 1995)
Figure 1.3. Road map of the study area. The rectangle defines the boundaries of the study region. Towns shown include Bellevue, Bloomville, Clyde, Fremont, Green Springs, Greenwich, Huron, Sandusky South, Tiffin, and Willard. The circular feature southeast of Bellevue is the Bellevue Reservoir. (Modified from the United States Census Bureau, State and County Quick Facts area maps, 1990)

The northern boundary of the study area is at 900 ft and the southern boundary is at 920–930 ft. The width of the Defiance Moraine varies from approximately 4.2 to 5.6 miles within the study area.

Physiographic regions of the study area include the Huron-Erie Lake Plains section and the Till Plains section (Figure 1.4). The Huron-Erie Lake Plains section contains the following districts in the study area: Maumee Lake Plains, Bellevue-Castalia Karst Plain, and the Lake Erie Plain (Brockman, 1998). The Maumee Lake Plains is a lake basin of low relief (5 feet) composed of Pleistocene-age silt, clay, and
Figure 1.4. Physiographic regions of Ohio. The enlarged area illustrates the detailed physiography of the study area. (Modified from Brockman, 1998)
lake-planed till. Landforms common to the area are beach ridges, bars, dunes, deltas, and clay flats (Brockman, 1998). The Bellevue-Castalia Karst Plain is a hummocky karst region that straddles both the lake plain (7.6a) and till plain (7.6b). Unit 7.6a contains Wisconsinan lake sediments and lake-planed till. Unit 7.6b contains a thin Wisconsinan till over limestone (Brockman, 1998). The Erie Lake Plain is a very low relief (10 feet) lake basin separated from modern Lake Erie by shoreline cliffs. This district is composed of Pleistocene age lacustrine sand, silt, clay, and lake-planed till (Brockman, 1998).

The Till Plains section of the study area contains the Central Ohio Clayey Till Plain district (Figure 1.4). The district is a region of clayey, high-lime till with a northeastern source. The late Wisconsinan till was deposited from the Erie Lobe about 22,000 to 16,000 years ago. The region has a moderate relief of 100 feet. Flat ground moraine and intermorainal lake basins separate end moraines. There is limited outwash and thin to no loess cover (Brockman, 1998).

The physiography furnishes information about the soil regions that have developed in Ohio. The soil map of Ohio (Figure 1.5) was compiled from detailed county soils maps. Different groupings or associations of common soil series were identified and combined into the twelve regions depicted in Figure 1.5 (Ohio Department of Natural Resources, Division of Soil and Water Conservation, 1999). Soil regions of the study area include the Hoytville-Nappanee-Paulding-Toledo soil association (Region 1), the Blount-Pewamo-Glynwood association (Region 3), and the Bennington-Cardington-Centerburg association (Region 5). The soils in each region of the study area were analyzed for five basic soil characteristics to provide a general overview. The results are summarized in Table 1.1.
Figure 1.5. Soil map of Ohio. (Modified from the Ohio Department of Natural Resources, Division of Soil and Water Conservation, 1997.)
Table 1.1. Percentage of Soils in Each Soil Region with Specific Characteristics. (Modified from the Ohio Department of Natural Resources, Division of Soil and Water Conservation Division, 1997.)

The soils were an important part of this study because soils indicate the type of glacial deposit present. Soils that develop in glacial deposits contain characteristics of that material. Variations in the soils indicate the type of glacial deposit present, and may even indicate different tills (Forsyth, 1965). The composition and ages of tills can be inferred from the soils (Goldthwait et al., 1965). In this study, the most common soils developed in glacial deposits that overlie limestone and dolomite bedrock. Therefore, the soils have a relatively high lime content in the substratum (Ohio Department of Natural Resources, Division of Soil and Water Conservation, 1999).

**Regional Bedrock Geology**

The bedrock stratigraphy of north-central Ohio is predominantly Silurian and Devonian limestones and dolomites, with some shales and sandstones (Figure 1.6). Detailed bedrock geology of the study area is illustrated in Figure 1.7. The Silurian rocks in the study area belong to the Niagara Group and the Bass Islands Group (Orton and Peppel, 1906; Stout, 1941). The Niagara Group contains the following formations from oldest to youngest (Figure 1.8): Dayton Formation, Rochester Shale, and Lockport.
Figure 1.6. Bedrock map of Ohio. (Modified from the Ohio Department of Natural Resources, Division of Geologic Survey, 1998)
Figure 1.7. Bedrock geology map of the study area (1:500,000 scale). *The term Monroe Formation has been abandoned. This formation is now considered as including both the Bass Islands Group and the Detroit River Group. In north-central Ohio, the Monroe Formation spans from the base of the Greenfield Dolomite to the base of the Columbus Limestone (Dennis Hull, pers. comm., 2000) Modified from Bownocker, 1992.
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Figure 1.8. Stratigraphic column of the bedrock units in north-central Ohio (After Hull, 1991; Coogan, 1996; Hull, pers. comm., 2000)
Formation (Stout, 1941; Hull, 1991). The Dayton Formation is an even-bedded crystalline dolomite averaging 8 feet in thickness. The Rochester Shale is a soft, calcareous and ferruginous shale that averages 40 feet in thickness. Locally, thin dolomitic layers may be present (Stout, 1941). The Lockport Formation is composed of undifferentiated dolomites (Hull, 1991) which tend to be massive and highly crystalline (Stout, 1941).

The Bass Islands Group contains, from oldest to youngest (Figure 1.8):
Greenfield Dolomite, Tymochtee Dolomite, undifferentiated dolomites, Bass Islands Dolomite, and Helderburg Limestone (Stout, 1941; Hull, 1991). The Greenfield Dolomite is dense and hard; it ranges from flaky layers to massive (Stout, 1941). This formation, 175 to 225 feet thick, is mostly covered by glacial drift and is only found at the surface in southern Ohio (Stout, 1941). The Tymochtee Dolomite is approximately 125 to 175 feet thick and occurs as thin layers to massive beds. This formation is widely distributed over much of northwestern Ohio and has been characterized as dense, tough, coarsely crystalline, porous, and cavernous (Stout, 1941). The undifferentiated dolomite formation grades into a dolomite with some thin layers of shales and evaporite minerals such as halite, anhydrite, and gypsum (Hull, 1991). The Bass Islands Dolomite and Helderburg Limestone do not occur in north-central Ohio due to an unconformity (Hull, 1991).

The rocks of the Devonian System in the study area (Figure 1.8) are the Amherstburg Dolomite, Lucas Dolomite, Columbus Limestone, Delaware Limestone, and Olentangy Shale (Stout, 1941; Hull, 1991). The oldest Devonian rocks were removed by erosion to form an unconformity (Hull, 1991). The Amherstburg Dolomite
is massive with an open to cavernous texture. The formation is 50 to 75 feet thick (Stout, 1941). The Lucas Dolomite, having an irregular thickness, is a bedded dolomite that is calcareous in some localities (Stout, 1941). The Columbus Limestone is massive, 80 to 125 feet thick, and locally contains chert. The composition of the limestone varies horizontally and vertically, with the lower part being a limy dolomite and the upper part a low-magnesian limestone (Stout, 1941). The Delaware Limestone varies from a shale with thin limestone layers to a massive limestone with partings of shale (Stout, 1941). This limestone is 30 to 70 feet thick and is fossiliferous (Stout, 1941). The Olentangy Shale is a gray, siliceous, and calcareous shale about 15 to 30 feet thick (Stout, 1941). In north-central Ohio this formation is divided into the lower Plum Brook Shale and the upper Prout Limestone (Hull, 1991).

In the study area, the older Silurian rocks outcrop in the west and younger Devonian rocks outcrop in the east. The sequence of exposed rocks is due to the location of the study area on the eastern flank of the Findlay Arch (Figure 1.9). In Seneca County the rocks dip east at approximately 28 ft/mi (Stout, 1941). Rocks of the Niagara Group occur in the western part of Seneca County, with the eastern boundary at the town of Green Springs on Figure 1.3 (Orton and Peppel, 1906). A layer of green shale and bituminous matter 1 to 6 inches thick marks a disconformity between the Niagara Group and Bass Islands Group (Stout and Lamey, 1940). This shale, according to Stout and Lamey, was liberated from the carbonate residue through solution and then deposited as residual debris. The Bass Islands Group and Detroit River Group outcrop over much of central Seneca County as a wedge-shaped area 4 to 5 miles wide in the north and 8 to 9
Figure 1.9. Structural geology map of Ohio with ages of rocks labeled. Modified from Coogan, 1996.

miles wide in the south (Orton and Peppel, 1906). The Columbus Limestone occurs in the east along local exposures from Republic to Bellevue (Figure 1.3); the Delaware Limestone outcrops in the easternmost section (Stout, 1941).

Huron County has very few rock outcroppings because the county is located far down on the eastern flank of the Findlay Arch and mostly because of the thick glacial drift cover (Stout, 1941). However, Columbus and Delaware Limestones occur in the northwest corner of the county. In fact, Columbus Limestone underlies the city of Bellevue where extensive quarrying has taken place (Stout, 1941).

In Erie County the rocks dip southeast at approximately 24 ft/mi due to the position of the rocks on the Findlay Arch. From west and east, and oldest to youngest the
units are as follows: Bass Islands Group, Detroit River Group, Columbus Limestone, and Delaware Limestone (Stout, 1941). The Columbus and Delaware Limestones occur at or near the surface throughout much of the county and particularly in the northwest corner. In the early 1900’s, Erie County was one of the leading stone and lime producers in the state due to the occurrence of the limestones (Orton and Peppel, 1906).

The western part of Sandusky County is located near the crest of the Findlay Arch and thus the rocks dip east at about 17 ft/ mi (Stout, 1941). There are numerous bedrock outcrops because the drift cover averages less than 25 feet. The Lockport Formation of the Niagara Group outcrops in the west; the Bass Island Group outcrops in the central region (Stout, 1941). The Lucas Dolomite of the Detroit River Group outcrops (where not covered by drift) in a narrow belt in the east and the Columbus Limestone outcrops only in the southeast near Bellevue (Stout, 1941). The Columbus Limestone is quarried near Bellevue and caverns have been found beneath the quarries (Orton and Peppel, 1906). The cavern is evidence of the karst activity that predominately occurs in the Columbus Limestone (Hull et al., 1998) and that plagues much of central and southern Ohio (Pavey et al., 1998).

The study area is located in a region known as the Bellevue-Castalia Karst Plain. This region includes northeastern Seneca County, northwestern Huron County, southeastern Sandusky County, and western Erie County (Figure 1.10). Ohio karst regions are defined as areas that lie within one-half mile of known karst features and are underlain by carbonate bedrock (Hull et al., 1998). The Bellevue-Castalia Karst Plain is a region of mature karst development that contains the most sinkholes of the all the karst regions in Ohio (Hull, 1999).
Figure 1.10. Map of the probable karst regions of the Bellevue-Castalia Karst Plain. 1:500,000 scale. Areas labeled P are probable karst areas, the area labeled C is dominated by carbonate bedrock, and the area labeled S is interbedded limestones and shales. Modified from Pavey et al., 1999a.
Karstification in the study area is due to dissolution of the anhydrite and gypsum layers of the Bass Islands Group undifferentiated dolomites (Figure 1.8). Groundwater enters the anhydrite layers from fractures in the overlying carbonate rocks. The water reacts with the anhydrite to form gypsum, increasing the volume by 33 to 66 percent (Hull, 1999). The overlying carbonates fracture from the swelling, allowing more groundwater to enter the layers of evaporites. This water dissolves the gypsum; the Devonian carbonates then collapse or breakdown (Hull, 1999). This process has created a mature karst region with perceptible surface relief of as much as 20 feet in the glacial drift (Hull et al., 1998).
CHAPTER 2

GLACIAL GEOLOGY

Glacial History of Ohio

The Quaternary geology in Ohio consists of glacial deposits from the continental
ice sheets of the Pleistocene. The Laurentide Ice Sheet advanced into Ohio several times
during the Pleistocene (Richmond and Fullerton, 1986), leaving behind till sheets, loess,
and lake deposits that transformed the geomorphology and topography of the state.
Dating of the glaciations has been difficult and the classic interpretation of four
Pleistocene glaciations (Table 2.1) generally has been abandoned in the Midwest. The
marine oxygen isotope record, which indicates the volume of land ice, fundamentally
changed the theory of the Ice Age from the classical four glacial/interglacial cycles
during the Pleistocene to many cycles during the Quaternary (Johnson et al., 1997). Even
with refinement of the marine oxygen isotope record, many problems remain with
classification and correlation of terrestrial glacial events. For example, the oxygen
isotope record may indicate a change in ice volume that does not correspond to other
evidence, such as sea level fluctuations recorded by coral reefs (Peteet et al., 1992).

Other methods of dating and correlation are also problematical. The complex
nature of the stratigraphic sequences, particularly in type sections in Illinois, Iowa, and
Nebraska has led to difficulties in correlation across the midcontinent (Richmond and

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<table>
<thead>
<tr>
<th>Glacial and Interglacial Cycles</th>
<th>Initiation of Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wisconsinan Glacial</td>
<td></td>
</tr>
<tr>
<td>Woodfordian (advance)</td>
<td>23,000 years B.P.</td>
</tr>
<tr>
<td>Farmdalian (retreat)</td>
<td>28,000 years B.P.</td>
</tr>
<tr>
<td>Aftonian (advance)</td>
<td>40,000 years B.P.</td>
</tr>
<tr>
<td></td>
<td>75,000 years B.P.</td>
</tr>
<tr>
<td>Sangamorian Interglacial</td>
<td>125,000 years B.P.</td>
</tr>
<tr>
<td>Illinoisian Glacial</td>
<td>250,000 years B.P.</td>
</tr>
<tr>
<td>Yarmouthian Interglacial</td>
<td>400,000 years B.P.</td>
</tr>
<tr>
<td>Kansan Glacial</td>
<td>500,000 years B.P.</td>
</tr>
<tr>
<td>Aftonian Interglacial</td>
<td>600,000 years B.P.</td>
</tr>
<tr>
<td>Nebraskan Glacial</td>
<td>1.6 million years B.P.</td>
</tr>
</tbody>
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Table 2.1. The classic timeline of glacial and interglacial cycles of the Pleistocene with the approximate dates of the beginning of each stage in years before present (B.P.). After White (1982) and Henry Helenek (pers. comm., 1993).

Fullerton, 1986; Johnson et al., 1997). Also, these glacial units are time-transgressive and records of events in one area may not be synchronous with events in other areas (Johnson et al., 1997; Scott Brockman, pers. comm., 1999). The criteria for correlation of units across the Midwest provides yet another difficulty with the classic Ice Age designations. For example, paleosols have no chronologic control or significance on a regional scale, due to the diachronous nature of buried soils (Richmond and Fullerton, 1986). Thus, paleosols should only be used for local glacial history reconstruction (Richmond and Fullerton, 1986). Radiocarbon age estimates also lead to correlation problems. Approximately one-third of samples have a true age that is beyond one standard deviation of the reported age. Additionally, it has long been recognized that glacial entrainment and transportation can deposit older organic materials over younger in situ materials (Lowell, 1995). Poor chronologic and stratigraphic control of glacial units has provoked many glacial geologists to abandon the terms “Nebraskan”,

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"Aftonian", "Kansan", and "Yarmouthian" (Richmond and Fullerton, 1986; Johnson et al., 1997). Thus, midcontinent glaciations prior to the Illinoian are labeled as Pre-Illinoian (Johnson et al., 1997).

Regardless of the label or exact date, the Laurentide Ice Sheet formed over Labrador, Canada, and entered Ohio during Pre-Illinoian time (White, 1982). As the ice spread through Ohio, the Teays River in western Ohio was blocked, as was the Steubenville River in eastern Ohio (Fullerton, 1986). The Minford silt was deposited beyond the ice margin in southern Ohio, and the Calcutta silt was deposited in eastern Ohio (Fullerton, 1986). Pre-Illinoian deposits are only exposed in the extreme southwest part of the state (Figure 2.1). The ice advanced far south in western and central Ohio due to the flat-lying carbonates in the western portion of the state. The ice did not advance as far south in eastern Ohio because the topography was characterized by sandstone hills (Goldthwait et al., 1965). The ice advanced into Ohio again during the Illinoian Glaciation. Such deposits are exposed beyond the Wisconsinan glacial maximum in southern, central, and eastern Ohio (Figure 2.1). These Illinoian tills and silts have not been well studied; thus, there is little detail of the stratigraphy and no radiometric control (Frolking and Szabo, 1998; Fullerton, 1986).

According to Dreimanis and Goldthwait (1973), the ice sheet next advanced into Ohio during the early Wisconsinan and reached a maximum position in central Ohio. This interpretation was based on the inferred ages of tills in northern Ohio, near Cleveland. The till at the Cleveland site overlies a red paleosol that White (1982) assigned as Sangamon because the soil resembled red Sangamon soils in Illinois (Szabo, 1992). Therefore, an early Wisconsinan age was assumed for the till. However, the age
Figure 2.1. Glacial geology of Ohio. This map is a simplified version of the map by Goldthwait et al., 1961. (Modified from the Ohio Department of Natural Resources, Division of Geological Survey, 1997.)
of the paleosol has been reinterpreted as pre-Illinoian due to the degree of weathering (Szabo, 1992). The till near Cleveland is currently interpreted as Illinoian (Dreimanis, 1992; Fullerton, 1986).

A till unit can only be assigned as early Wisconsinan unequivocally if it is overlain by a unit of known middle Wisconsinan age and underlain by a unit of known Sangamon age (Dreimanis, 1992). There are no sections in the Lake Erie basin that fulfill this requirement (Dreimanis, 1992). Currently, there is no evidence to support early or middle Wisconsinan glaciation in northern Ohio (Szabo, 1992; Fullerton, 1986). In fact, the evidence suggests that the early and middle Wisconsinan was a long nonglacial period characterized by intense weathering (Fullerton, 1986). Also, ice volume curves indicate a dearth of ice volume needed to glaciate the midcontinent during this time (Szabo, 1997).

The main glacial advance occurred during the late Wisconsinan, as evidenced by the extensive nature of the glacial deposits (Figure 2.1). The ice sheet followed the depressions of the Great Lakes basins and entered the United States via these basins (Dreimanis and Goldthwait, 1973). Ohio was glaciated by the Huron-Erie Lobe, which split along the ice margin into several sublobes (Figure 2.2). The Huron-Erie Lobe is believed to have entered Ohio over 20,000 years ago: over 25,000 years B.P. (before present) according to Goldthwait et al. (1965); approximately 23,000 years B.P. according to Dreimanis and Goldthwait (1973); approximately 21,000 years B.P. according to Fullerton (1986) and Richmond and Fullerton (1986). The date of 21,000 years B.P. is supported by a study of the Miami Sublobe, which determined that the first late Wisconsinan ice advance of that lobe occurred about 20,000 years B.P. (Ekberg et
Figure 2.2. Diagram of the Laurentide Ice Sheet with glacial lobes and sublobes of the Great Lakes basins during the late Wisconsinan maximum glaciation. Arrows indicate directions of inferred ice flow. (Fullerton, 1986)
al., 1993). The ice margin of the sublobes fluctuated and deposited a sequence of tills that indicate several episodes of ice advancement. Recent studies have suggested that a minimum of four major ice advances occurred during the late Wisconsinan (Frolking and Szabo, 1998; Pavey et al., 1999b; Fullerton, 1986).

Glacial History of the Study Area

The study area, at the junctions of Erie, Huron, Seneca, and Sandusky counties, is in the northeastern portion of the Scioto Sublobe. Although the sublobes did not advance and retreat simultaneously throughout the Late Wisconsinan (Dreimanis and Goldthwait, 1973), recent studies suggest that several of the Huron-Erie Sublobes advanced in unison from approximately 21,000 to 18,000 years B.P. (Fullerton, 1986; Ekberg et al., 1993). During this time the Boston Till, Lower Caesar, Middle Caesar, and Upper Caesar Tills were deposited in the Scioto Sublobe (Figure 2.3). At the same time, the Navarre Till was deposited along the Killbuck Sublobe. Although the study area is in the Scioto Sublobe, the tills of the eastern Scioto Sublobe are named and correlated to the Killbuck Sublobe tills (Frolking and Szabo, 1998; Szabo and Totten; 1995). Thus, the earliest late Wisconsinan till in the study area is the Navarre Till, which consists of several sandy and somewhat pebbly till units (White, 1961) that were deposited from approximately 21,000 to 15,500 years B.P. (Figure 2.3). The magnitude and ages of the advances have not been determined (Fullerton, 1986).

Laminated clays that overlie the Navarre Till in Seneca County are likely Erie Interstade deposits (Dreimanis and Goldthwait, 1973). This interstade occurred approximately 15,500 years B.P. when the Huron-Erie Lobe retreated into Canada (Dreimanis and Goldthwait, 1973; Fullerton, 1986). The Erie Interstade was followed by
Figure 2.3. Chart correlating the glacial units of the Michigan, Huron-Erie, and Ontario-Erie Lobes. (Fullerton, 1986).
another advance of the Huron-Erie Lobe that deposited the Haynesville Till, a silty, thin (<10 feet) drift sheet (White, 1961). Another interstadial occurred approximately 15,300 years B.P. in which the Huron-Erie Lobe retreated into Canada, possibly as far north as the Huron Basin (Fullerton, 1986). Proglacial lakes again formed in the basins. As the ice margin readvanced into the United States, the suture between the Huron-Erie and Ontario-Erie Lobes had shifted westward to the western end of the Erie Basin, resulting in glaciaion of northern Ohio by the Ontario-Erie Lobe. The advancing ice incorporated the lacustrine sediments of the proglacial lakes and deposited the clay-rich Hiram till (Goldthwait et al., 1965). The Hiram Till is thin, often less than 10 feet, but thickens westward (White, 1960) and the clay content decreases southwestward (Dreimanis and Goldthwait, 1973).

As this ice retreated from Ohio about 14,500 years ago (Calkin and Feenstra, 1985), the ice margin blocked drainage to the north and the Ohio divide blocked drainage to the south (Forsyth, 1959), thus forming proglacial lakes in the Erie Basin. The first lake was Lake Maumee I which formed in the southwestern part of the Erie Basin and is characterized by beach deposits at an elevation of 800 feet (Forsyth, 1959). The Maumee beaches have a relief of 5 to 10 feet and are approximately 500 to 1500 feet wide (White, 1982). The Maumee I beaches are not well developed and are only easily recognizable west of Toledo, Ohio (Forsyth, 1959).

As the ice continued to retreat a new lake, Maumee II, was formed at a lower elevation of 760 feet (Forsyth, 1959). Although the Maumee II beaches span most of northern Ohio, the beaches are not topographically prominent. According to Forsyth and Leverett and Taylor (1915), the low topography is attributable to this beach being
overridden by a subsequent lake, Maumee III, when the ice sheet readvanced slightly. The theory of oscillating lake levels by Leverett and Taylor (1915) was based on their observations that the Maumee II beach had a washed look characteristic of submergence by water. Submerged beaches have lower than normal relief, higher than normal clay content, stiff soil, and are characteristicly fragmentary or absent in places (Leverett and Taylor, 1915). However, Calkin and Feenstra (1985) cited studies where no evidence was found to support fluctuating lake levels, and a descending sequence of lake levels was suggested. Totten (1985) also noted a lack of evidence supporting the submergence of the beaches: (1) submerged beaches would have been at least partially removed by wave action, (2) sediment entering the lakes would have been trapped by the old beaches and partially buried the beach, (3) silty deposits should cover submerged beaches, and (4) the clay matrix of the beaches was probably derived from the shale bedrock in eastern Ohio and not from the lacustrine deposits. The “submerged” beaches do not meet these criteria and Totten (1985) called for a descending chronology.

Regardless, the Lake Maumee III beach occurs at an elevation of 780 feet. The beach is extensive and has the greatest relief of the Maumee beaches (Forsyth, 1959). It occurs along the entire length of the Erie Basin and indicates that the ice margin had retreated out of Ohio by this time (Forsyth, 1959), approximately 14,500 years B.P. (Fullerton, 1986) to 14,100 years B.P. (Totten, 1985).

The ice never returned to Ohio. The ice retreated northward and the lakes in the Erie and Huron Basins joined to form Lake Arkona (Calkin and Feenstra, 1985) that was three times larger than present day Lake Erie (Leverett, 1902). The beaches of this lake are at an elevation of 710 feet (Forsyth, 1959; Calkin and Feenstra, 1985). Two lower
levels, Arkona II and Arkona III, are at elevations of 700 feet and 695 feet, respectively (Calkin and Feenstra, 1985; White, 1982). All three beaches are poorly developed and they are discontinuous across northern Ohio (Forsyth, 1959). Forsyth attributed this obscurity to a continuous lowering of the lake level by erosion of the drainage outlet and submergence by a later lake, Whittlesey. Totten (1985) supported a topographically descending chronology of beaches and placed Lake Arkona after Whittlesey.

Whittlesey beaches formed at an elevation of 735 feet when a readvance of the ice sheet blocked the Arkona drainage outlet (Forsyth, 1959) approximately 13,000 years B.P. (Calkin and Feenstra, 1985). The Whittlesey beaches are the most prominent and highest in northern Ohio, especially in the eastern Erie Basin where the fetch was greater (Forsyth, 1959). In the northeast the Whittlesey beaches reach heights of 70 feet whereas the beaches in northwestern Ohio are only 10 to 15 feet high (Forsyth, 1959). Calkin and Feenstra (1985) suggested that the higher beaches in the east are attributable to rising waters encountering the rebounding land of the northern basin. Totten (1985) suggested the prominence of the beaches was due to the beach position on a wave-cut cliff.

A major retreat occurred that dramatically lowered the lake, possibly to a level below present day Lake Erie (Forsyth, 1959). A minor readvance occurred to form another proglacial lake, Wayne, at an elevation of 660 feet. These beaches are indistinct and lacking in many areas due to submergence by Lake Warren, which developed beaches at 680 feet (Forsyth, 1959). The Warren beaches are the most extensive and last of the proglacial lake beaches (Forsyth, 1959; Calkin and Feenstra, 1985). These beaches are distinctly sandy with little gravel and in many places occur as multiple ridges of dunes and beach sand (Forsyth, 1959; Calkin and Feenstra, 1985).
Studies conducted since Forsyth (1959) do not support Lake Wayne as older than Lake Warren. Calkin and Feenstra (1985) concluded that Lake Warren formed as the ice retreated from Lake Whittlesey. Lake Whittlesey drained along the ice margin into the Saginaw Bay area of the Huron Basin. The proglacial lake in the Huron Basin joined with the draining Lake Whittlesey to form Lake Warren. Wood from below the Warren beaches was dated at 13,050 ± 100 years B.P. (Calkin and Feenstra, 1985; Totten, 1985), which is consistent with Lake Whittlesey occurring about 13,000 years B.P. Also, the Wayne beaches only show evidence of submergence in Michigan, and the Ohio beaches are discontinuous in the west and occur as wave-cut surfaces in the east. As such, the Wayne beaches may in fact be offshore bars of Lake Warren (Calkin and Feenstra, 1985).

The last of the proglacial lakes was Lake Lundy, which is characterized by three levels: Grassmere at 640 feet, Dana at 620 feet, and Elkton at 615 feet (Forsyth, 1959). All three are sandy, have low relief, and are discontinuous at best (Forsyth, 1959; Calkin and Feenstra, 1985). For these reasons, the beaches have only been mapped locally (Forsyth, 1959) and may actually represent bars of earlier beaches or windblown sand (Calkin and Feenstra, 1985).

Glacial Geology of the Study Area

The glacial geology of the study area is primarily late Wisconsinan till and lake deposits. The 1961 glacial map of Ohio (Figure 2.1) identified only broad groupings of deposits: kames and eskers, outwash, lake deposits, Wisconsinan ground moraine, Wisconsinan end moraine, undifferentiated Illinoian, and undifferentiated pre-Illinoian. Knowledge of the glacial deposits is vital to understanding the hydrology, soils, and other environmental facets of the area. Also, many aspects of community life are dependent
upon the surficial geology in the Great Lakes region; comprehension of the surface and near-surface processes is needed to understand the Earth-human interaction (Groat, 1999). For these reasons, current glacial maps are important.

The Ohio Department of Natural Resources (ODNR) Division of Geological Survey recently has completed a glacial map of Ohio (Pavey et al., 1999b) that provides more detailed information than the 1961 map. The 1999 map contains many more units than the earlier glacial map. Although the new glacial map is not yet available in a digital format, the 1:250,000 scale maps comprising the state glacial map are available digitally from the Ohio Geological Survey website, and the study area is contained within the 1:250,000 Toledo Quadrangle (Pavey and Goldthwait, 1993). This map contains the same information as the 1999 Ohio glacial map, just at a larger scale.

The glacial geology of the study area (Figure 2.4) is composed of Holocene water and alluvium, late Wisconsinan lacustrine sediments, and late Wisconsinan tills. The late Wisconsinan (23-13 ka) lacustrine sediments in the area are beach ridges, lake sand, lake silt, and lake clay (Pavey and Goldthwait, 1993). The beach ridges formed along the shores of former glacial lakes and are composed of fine sand to coarse gravel and cobble deposits. These beaches may include areas of small dunes or nearshore bars (Pavey and Goldthwait, 1993). The southernmost beach in the study area is Maumee III (Figure 2.4). The discontinuous beach segments along the eastern margin of the Figure 2.4 are remnants of the Maumee beaches. This irregular strandline is likely due to the occurrence of small islands of low bedrock knolls and hills during Lake Maumee time (Leverett, 1902). The Whittlesey beach occurs just north of the Maumee III beach. The Whittlesey beach enters the study from the west and extends toward the northeast.
Holocene (Recent) 10 ka to present
  w water (The circular water feature is the Bellevue Reservoir)
  a alluvium

Late Wisconsinan; water-deposited units
  B beach ridges
  LS lacustrine sand
  LL lacustrine silt
  LC lacustrine clay

Late Wisconsinan, Late Woodfordian; ice-deposited units - Clayey till (Hiram)
  G4 ground moraine
  L4 lake-planed moraine
  M4 end moraine

Figure 2.4. Quaternary geology of northern Ohio with selected beach and end moraine labels. Modified from the Toledo 1:250,000 Quadrangle (Pavey and Goldthwait, 1993). See Figure 1.3 for location of reservoirs and cities with roads.
beach terminates abruptly in the northern section of the study region. During the time of the Whittlesey lake, a bay was present in the northeast corner of the study area. The shallow water and presence of islands precluded the formation of distinct beaches in this region (Leverett, 1902). The northernmost beach belongs to Lake Warren, a ridge of sandy gravel with a height of about 10 feet (Leverett, 1902).

The lacustrine sand was deposited in the glacial lakes as shallow water deltas or nearshore bars or sheets. This unit may also contain some areas of small dunes (Pavey and Goldthwait, 1993). Lacustrine silts were deposited in low-velocity water of glacial and slackwater lakes. These silts, which may contain fine sand or clay, are well-laminated in distal portions of deltas and poorly laminated elsewhere (Pavey and Goldthwait, 1993). Lacustrine clay was deposited in calm water of the glacial lakes and the deposits are mostly laminated. Thin organic deposits in some places cover the clays (Pavey and Goldthwait, 1993).

The late Wisconsinan (late Woodfordian, 18-14 ka) till deposits in the study area are the clayey Hiram Tills (White, 1961). The ground moraine is flat to gently undulating while the end moraine occurs as a hummocky ridge somewhat higher in elevation than the adjacent terrain (Pavey and Goldthwait, 1993). The ground moraine (Figure 2.4, unit G4) drift is not very thick in the study area. The thickness is about 50 feet in the southern portions and thins to the north (Leverett, 1902). Ravines incised to a depth of 10 to 20 feet often have bedrock outcroppings (Leverett, 1902).

The end moraine is the Defiance Moraine (Figure 2.1 and 2.4). This moraine has a low, broad profile. The moraine is two miles wide (often greater than 4 miles) and crests 20 to 50 feet above the surrounding terrain (Leverett, 1902). The slope on the
proximal side is quite gentle (Leverett, 1902), and debate continues as to the exact northern boundary (Mike Angle, pers. comm., 1999). The extensive karstification of the area may contribute to this confusion. According to Forsyth (1959) and Leverett (1902), the Defiance Moraine (Figure 2.4, unit M4) was deposited contemporaneously with Lake Maumee I. However, later studies found that the Hiram Till occurs only in the upper part of the Defiance Moraine (White, 1960) and that the moraine must have formed prior to Lake Maumee I (Calkin and Feenstra, 1985; Totten, 1985).

The lake-planed moraine is a very flat unit of ground moraine that was planed by waves in glacial lakes. In places, patches of sand, silt, or clay overlie this planed moraine (Pavey and Goldthwait, 1993). The thickness of the Hiram Till is similar on the till plain (ground moraine) and lake plain (lake-planed moraine and lacustrine sediments). The similarity of drift thickness indicates that extensive erosion by wave action did not occur after the last glaciation (Totten, 1985).
CHAPTER 3

METHODS

Data Acquisition

The Landsat-5 satellite acquired the TM image used in this study on June 11, 1984 at approximately 9:30 am local time (see Appendix A for Landsat-5 specifications). Dr. Robert Vincent of Bowling Green State University in Bowling Green, Ohio donated the quarter scene. Copyright laws did not pertain to this imagery because Ohio State University and Bowling Green State University are both members of OhioView. OhioView is a consortium of educational institutions in Ohio that is supported by the USGS Earth Resource Observation Systems (EROS) Data Center and the National Aeronautics and Space Administration (NASA) Glen Research Center to provide rapid and inexpensive Landsat TM imagery to participating institutions (Lein, 1999).

A digital glacial map of Ohio was obtained from the ODNR Division of Geological Survey ftp (file transfer protocol) website, accessible through the Geological Survey homepage www.dnr.state.oh.us/odnr/geo_survey. The Quaternary map of Ohio, Toledo 1:250,000 sheet (Albers Conical Equal Area projection) was used for the study.

The image was geometrically rectified using 7.5 minute (1:24,000 scale) hydrography digital line graphs (DLG). The DLGs were obtained from the USGS EROS Data Center Global Land Information System website via anonymous ftp,
http://edcwww.cr.usgs.gov/webglis. The nine DLGs, projected as Universal Transverse Mercator (UTM) Zone 17, were mosaicked to form the reference map for image rectification (Figure 3.1). The transportation network is more apparent on the Landsat TM image than the stream network. However, the USGS transportation DLGs could not be used because the point attribute tables were missing. Without these tables the DLGs cannot be mosaicked.

**Image Analysis**

The image was processed using ERDAS Imagine 8.3 software on a UNIX workstation. Analysis of an entire quarter scene of Landsat TM imagery is both inefficient and inexpedient. As evident in Figure 1.1, the geographical expanse of the quarter scene does not allow for detailed geologic mapping. Also, computer processing time is dramatically increased for such a large image. For these reasons, a subscene was generated from the image.

This subset image was examined using image enhancement techniques to extract the maximum glacial information. After viewing numerous false-color composite combinations, contrast stretching and convolution filtering techniques were employed. Feature selection was then performed. These specific methods and their results are explained in detail in Chapter 4, which is a paper written by the author and two other contributors (Dalton-Sorrell et al., 1999) that was presented at the Pecora 14/Land Satellite Information III Conference in Denver, CO in December, 1999.

After this initial assessment, the image was atmospherically and radiometrically corrected for integration with the digital glacial map. Examination of the histograms for each band indicated atmospheric attenuation. This scattering resulted in the hazy
Figure 3.1. Mosaic of the 7.5 minute DLGs in north-central Ohio used for geometric correction of the Landsat TM image. The map projection (UTM Zone 17) is the cause of skewness in this figure. The rectangle in the Watson DLG is a reservoir.
appearance of the false-color composites. Dark objects such as water have essentially zero reflectance of near-infrared wavelengths (Lillesand and Kiefer, 1994), whereas visible wavelengths have a greater observed reflectance due to atmospheric scattering (Jensen, 1996). The effects of atmospheric attenuation in the image were reduced through histogram adjustment, a process of shifting the affected bands to the left so the dark object reflectance is zero.

The image was geometrically rectified to the map for transformation of the image into map coordinates. The USGS 7.5 minute hydrography DLG mosaic (Figure 3.1) was used as the map projection source. Ground control points (GCPs) from the map are used for this process because the GCPs are features of known ground location that can be easily identified on the imagery (Lillesand and Kiefer, 1994). The GCPs of the image were located using file coordinates (row, column) and the map GCPs were determined by UTM coordinates in meters. A least-squares regression analysis was used to determine the spatial transformation equation of the image. The root-mean-square (RMS) error was examined before the transformation was applied. The RMS error indicates distortion that has not been corrected for by the transformation (Jensen, 1996). The transformation equation is not applied until the RMS error is less than the required threshold. A total RMS error of ≤ 1 pixel is acceptable for most scientific applications (Carolyn Merry, pers. comm., 1999). For this project, 48 GCPs (Figure 3.2) were used with a total RMS error of ± 1.2927 pixels and a total check point error of ± 0.8579 pixels (Appendix B.). A lower RMS error was not achievable using the mosaicked hydrography DLG because of insufficient points that could be reliably located on both the DLG and the image.

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Figure 3.2. Geometrically corrected (7,4,1) (red, green, blue, respectively) false-color composite of the study area. The GCPs used for rectification are plotted as large dots.
The spatial transformation process requires that the image be resampled to ascertain the pixel values of the geometrically corrected image. Nearest neighbor interpolation was used to resample the image to retain the radiometry. This interpolation scheme uses the nearest pixel value of the original image to determine the pixel value of the output image (Jensen, 1996). This method is preferred in the earth sciences because the pixel brightness values are not altered and the radiometry is retained. The mosaicked hydrography DLG was overlain on the resampled image to verify consistency of the geometric transformation (see Appendix C for true-color and color infrared images).

After radiometric and geometric corrections, image enhancement techniques such as band ratioing and principal component analysis were performed. These enhanced images were integrated with the digital glacial map for comparison. See Chapter 5 for details of these methods and results.

Other Methods

Several traditional methods were utilized to investigate discrepancies between the Landsat image and the glacial map. The glacial map was the primary source of ground truth data but did not account for all the information recorded by the Landsat sensor. Aerial photographs and topographic maps were examined for topographic and geomorphologic information, and county soil survey reports provided detailed information of the soil surface layer. The above data were verified through field checking.
CHAPTER 4

DELINEATION OF THE GLACIAL GEOLOGY OF NORTH-CENTRAL OHIO USING IMAGE ENHANCEMENT TECHNIQUES ON LANDSAT TM DATA

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ABSTRACT

The purpose of this study was to delineate the glacial geology of north-central Ohio using image enhancement techniques and feature selection on Landsat TM data. Glacial mapping with Landsat TM data has not been fully examined. Full comprehension of the glacial geology is vital to understand the environment, economy, and community life of the Great Lakes region. A contrast stretch (histogram equalization) of (5,4,3), (7,4,1), and (7,5,1) false-color composites all provided spectral discrimination of the glacial geology. Drainage patterns were best determined from a contrast stretch (histogram equalization) of band 4. Determination of drainage types provided the needed

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information to differentiate till from lake sediments. Convolution filters used on band 4 and the false-color composites did not provide additional detail of the glacial geology. None of the image enhancement techniques employed differentiated between end and ground moraines.

INTRODUCTION

The purpose of this investigation was to conduct feature selection and image enhancement on Landsat Thematic Mapper (TM) data to map glacial deposits and landforms in north-central Ohio. The image was analyzed to determine the spectral bands and the image enhancement techniques that would be most useful. The literature indicates that, for geologic purposes, any band combination should include TM bands 5 and/or 7 as these bands provide the greatest discrimination of lithologic materials (Crippen, 1989). Moreover, any band combination that excludes these bands will provide poorer information of the geologic features being examined (Crippen, 1989). According to Elson (1980) glacial features are more readily distinguishable in TM bands 4, 5, 6, and 7. With this in mind, a TM image of north-central Ohio was examined to determine the band combinations and enhancement techniques that were the most useful for delineating various glacial units.

The satellite remote sensing literature addressing glacial geology studies is sparse. Glacial geologists have extensively used aerial photography for mapping glacial deposits and landforms, but the use of satellite imagery for the same purpose has been limited. In the infancy of satellite remote sensing, glacial geologists attempted to use TM data for glacial geology oriented studies, but they concluded the images were useless unless the interpreter had a detailed knowledge of the region’s glacial geology. According to these
geologists, aerial photography provided better information (Elson, 1980). These geologists had a logical basis for their conclusions: their studies in the applicability of satellite imagery for glacial geology employed visual interpretation of single bands only. Elson (1980) and the research he cited only looked at single bands with no image enhancement techniques, no true- or false-color composites, or any other data analysis techniques. Single spectral bands contain a limited portion of the electromagnetic spectrum and these bands have a poorer spatial resolution than aerial photography. Aerial photographs receive more information from the electromagnetic spectrum, making aerial photographs more useful than satellite images. The results of these early studies has curtailed the interest in remote sensing for many glacial geologists (Elson, 1980).

Although the literature is limited, a number of geologists have utilized satellite images to aid in glacial geology studies. Clark (1997) suggests initially looking at single band images because some geologic features may be more apparent than on false-color composites. Day (1995) studied the distribution of drumlins and moraines in Nova Scotia, Canada using TM band 4. Landforms and till were delineated by using a contrast stretch technique and combined with knowledge of the soil moisture and vegetation type characteristics of these features. This enhanced image had a high degree of correlation with previously published surficial geology maps of the study area. Many studies have not been as successful in discriminating till types and end moraines (Clark, 1997); in fact, end moraines are seldom successfully detected on Landsat TM images (Elson, 1980).

METHODS

The Landsat quarter scene image, dated June 11, 1984, was first compared with the Quaternary map of Ohio (Pavey and Goldthwait, 1993). A subset image of the
quarter scene containing most of the glacial units was the focus of this study. A preliminary determination of the subset image was made using single bands. The subset image was then displayed as a series of false-color composites to determine which band combinations provided the most information regarding the glacial units. Several contrast stretch methods (histogram equalization, min-max, gamma) were employed and a few different convolution filters (low pass, high pass, edge detect) were run on the false-color composites to determine if additional glacial information could be extracted. Feature selection was then done. TM bands 3, 4, 5, and 7 provided the best discrimination of the glacial units. The thermal band (TM 6) did not appear to provide any pertinent information and was removed. Bands 1 and 2 did not reveal much information as to the areal extent of the geology in the study area. Therefore, band 2 was deleted, and band 1, although somewhat hazy, was retained due to usefulness in conjunction with bands 4, 5, and 7.

RESULTS

A variety of false-color composites were found to illustrate the glacial geology of the area effectively. The glacial geology consists mostly of till and lake deposits (Figure 4.1). The southern part of the study area is end moraine (M4 on Figure 4.1), and ground moraine (G4) is immediately to the north. Both the end and ground moraines are composed of a clayey till. Lake sands (LS), lake silts (LL), lake clays (LC), and lake-planed moraine (L4) characterizes the northern half of the image. Lake-planed moraine (L4) is ground moraine that was flattened by waves from glacial lakes. Due to the presence of the lakes, the lake-planed moraine has localized areas of sand, silt, or clay on the surface (Pavey and Goldthwait, 1993). The beach sand (B) corresponds to beach
Figure 4.1. Quaternary map of north-central Ohio, modified from the Toledo 1:250,000 sheet (Pavey and Goldthwait, 1993). Lacustrine silts are labeled LL, lacustrine clays LC, lacustrine sands LS, beach ridges B, lake-planed moraine L4, ground moraine G4, and end moraine M4.
ridges formed from the glacial lakes. There are three prominent beach ridges oriented northeast-southwest, and there are some discontinuous beaches in the northeastern section of the image.

A histogram equalization stretch of (5,4,3) as red, green, blue respectively (Figure 4.2) and (7,4,1) as red, green, blue respectively (Figure 4.3) false-color composites produced similar looking images that readily displayed the main glacial deposits: lake sediments, lake planed-moraine, beach deposits, and till. The glacial units were also detected on a histogram equalization stretch of a (7,5,1) image (Figure 4.4). Convolution filters (low pass, high pass) were also used on these images but did not provide any new information. End moraine was not distinguished from ground moraine, regardless of the image enhancement technique or feature selection employed.

An analysis of band 4 provided more information on drainage patterns than expected. The drainage patterns, which are an important aspect of glacial mapping, were more apparent in band 4 than the false-color composites. This band illustrates areas that are well-drained from areas that are poorly-drained. A histogram equalization stretch of band 4 (Figure 4.5) further emphasizes the drainage patterns. Tonal analysis of band 4 allowed for the discrimination between till and lake deposits. A 3 x 3 low pass filter produced similar results to the histogram equalization stretch, except that the smoothing effect was observed in the urban areas.

DISCUSSION

Band 4 and the false-color composites were compared with the Quaternary map of Ohio (Figure 4.1). These main units are discernable on the (5,4,3) image (Figure 4.2).
Figure 4.2. Histogram equalization of the Landsat TM (5,4,3) false-color composite of north-central Ohio. The cities of Clyde and Bellevue are labeled C and B, respectively. The lake plain is labeled L and the till plain is labeled T. Areas R and S do not correspond to any specific units; see text for explanation.
Figure 4.3. Histogram equalization of the Landsat TM (7,4,1) false-color composite of north-central Ohio. The cities of Clyde and Bellevue area labeled C and B, respectively. The lake plain is labeled L and the till plain is labeled T. Areas R and S do not correspond to any specific units; see text for explanation.
Figure 4.4. Histogram equalization of the Landsat TM (7,5,1) false-color composite of north-central Ohio. The cities of Clyde and Bellevue are labeled C and B, respectively. The lake plain is labeled L and the till plain is labeled T. Areas R and S do not correspond to any specific units; see text for explanation.
Figure 4.5. Histogram equalization of Landsat TM band 4 of north-central Ohio. The cities Clyde and Bellevue are labeled C and B, respectively. The lake plain is labeled L and the till plain is labeled T. Areas R and S do not correspond to any specific units; see text for explanation.
The lake silts have a uniform tone in the northwest corner (L in Figure 4.2), and till has a mottled tone in the south (T in Figure 4.2). The beach ridges are prominent due to their thin linear pattern, and the presence of roads along their crests.

The area in the center of Figure 4.2 is problematic. The city in the east is Bellevue (B) and the circular water structure at far center-right is the Bellevue reservoir. The city to the west is Clyde (C). The glacial deposits between these two cities are more difficult to classify. According to the glacial map, this area is lake-planed moraine with some sand deposits. As previously noted, lake-planed moraines often have spotty patches of lake sands, silts, or clays on the surface of this flattened ground moraine, or may be composed of a thin veneer of lake deposits overlying the till. Distinguishing lake-planed moraine from lake sediments and till is difficult because lake-planed moraine has characteristics of both lake deposits and till.

Another complication is the dark area immediately northeast of Bellevue (R in Figure 4.2). Area R does not correspond to any specific unit on the glacial map. It’s likely that the TM sensor has recorded a slight variation within the glacial cover. Glacial deposits are often heterogeneous; however, this heterogeneity does not warrant separation of the unit. Area R is a site of complicated glacial lake activity. In the area southeast of Bellevue (S in Figure 4.2) there are several small sections of beach ridges which resulted from a strandline being overridden by a later beach (Forsyth, 1959). The glacial lake processes that occurred in this area may have led to the glacial units’ variability such as organic matter content, drainage, and slight mineralogical changes.

The (7,4,1) false-color composite (Figure 4.3) illustrates the geology in a manner similar to that in Figure 4.2. Figure 4.3 does not have boundaries as sharp as those seen
in Figure 4.2. The (7,4,1) image may be more useful in mapping the glacial deposits because there appears to be less unit variability. For example, more even tones are depicted in Figure 4.3 than Figure 4.2 in the vicinity of area S. The mottled tones in Figure 4.2 may distract the interpreter from the glacial units as a whole to variability within the units.

A much different representation of the glacial geology is illustrated in the enhanced (7,5,1) false-color composite (Figure 4.4) than in Figure 4.3. However, the same units are represented: lake sediments, beach ridges, and till. Area R (Figure 4.4) is also dark toned, but the contrast with the surrounding ground moraine is less than in Figure 4.2 or 4.3. TM bands 5 and 7 are used for discriminating mineralogy and rock type (Lillesand and Kiefer, 1994) and for the detection of hydroxyl-bearing minerals (Crippen, 1989). Area R in Figure 4 corresponds with the dark tones in band 7. This area may contain a higher content of clay minerals, an hypothesis that is consistent with lake-planed moraine being overlain with lake sediments. The breaching of the beach could explain the presence of clays in the area.

According to the glacial map (Figure 4.1), end moraine is present along the southern edge of the image with ground moraine to the north. None of the false-color composites (Figures 4.2-4.4) or the image enhancement methods were capable of distinguishing end moraine from ground moraine. This result was expected as the two landforms are compositionally similar, and the spectral characteristics of the landforms are very similar. A more sophisticated analysis technique may be needed to provide distinction between ground moraine and end moraine.
Delineation of drainage types can aid in differentiating lake sediments from till. Discrimination between these deposits can be difficult because till and lake sediments are compositionally and spectrally similar (Clark, 1997). Band 4 (Figure 4.5) more clearly illustrates the drainage patterns of the sediments than the false-color composites and thus aids in delineating till from lake deposits. Image enhancement of Figure 4.5 indicates an unintegrated drainage (termed deranged drainage) in the southern part of the image. End and ground moraines commonly possess a deranged drainage. The lake sediments in the northwest portion of Figure 4.5 do not have this pattern, as they typically have an integrated drainage system.

CONCLUSIONS

For the purpose of mapping glacial geology, histogram equalization of (5,4,3), (7,4,1), and (7,5,1) false-color composites of Landsat TM data provides the best delineation of glacial units. Histogram equalization of band 4 provided details of drainage patterns and the drainage patterns can be used to discriminate between lake sediments and till. End and ground moraines were not distinguished using any of the image enhancement techniques tested in this study.

Although the enhanced false-color composites correlate fairly well to the glacial map, there are differences that need to be explained. The area between Clyde and Bellevue and east of Bellevue show spectral differences that do not correspond to known differences in glacial geology. Further analysis, such as band ratios and principal component analysis coupled with field data and soil surveys may provide answers to this
enigma. Also, landforms such as end moraines were not detected in the images, and separating end moraine from ground moraine of similar composition would be quite beneficial to glacial mapping.
REFERENCES CITED


CHAPTER 5

ASSESSMENT OF USING LANDSAT TM IN MAPPING THE GLACIAL GEOLOGY OF NORTH-CENTRAL OHIO

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ABSTRACT

The purpose of this study was to overlay Landsat TM imagery of north-central Ohio with a Quaternary map to assess the ability of satellite remote sensing data to delineate glacial geology. A (7,5,1) false-color composite provided more detail than a (7,4,1) composite for mapping clayey till. A ratio image of (7,7/1,4/5) (red, green, blue, respectively) depicts variations in the bare fields that could be used for detection of lake deposits and till. Variations in vegetation for lake-planed moraine and ground moraine were delineated using the ratio image. A principal component analysis (PCA) false-color

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composite of (PCA4, PCA3, PCA2) (red, green, blue) also portrays variations that occur in bare fields on glacial till. Manifest on the PCA image was a linear feature that appears to be a previously unmapped beach ridge.

INTRODUCTION

The purpose of this study was the integration of a 1:250,000 scale digital glacial map with Landsat TM imagery for improved mapping of glacial deposits and landforms in north-central Ohio. The TM image was processed to produce images that contain the greatest information on glacial geology. For geologic purposes, a band combination that includes band 7 combined with either TM bands 4 and/or 5 provide the greatest discrimination of lithologic materials (Crippen, 1989). Glacial features are most prevalent on TM bands 4, 5, 6, and 7 (Elson, 1980). Band ratios should be employed in any geological remote sensing endeavor because these ratios provide the greatest discrimination of surficial rocks and minerals (Aber et al, 1993). Principal component analysis provides subtle color variations which are useful in geologic studies (Jensen, 1996). With this in mind, the TM scene was examined using (7,4,1), (7,5,1), (7,7/1,4/5), and (PCA4, PCA3, PCA2) false-color composites to assess correlations between the features shown and the digital glacial map.

Glacial mapping has become a primary concern for the Great Lakes region. The state geological surveys of Ohio, Indiana, Illinois, and Michigan have joined in partnership with the USGS to produce more detailed surficial geology maps of the Great Lakes region. This union, the Central Great Lakes Geologic Mapping Coalition, sponsored a meeting in February, 1999 to discuss the importance of glacial mapping. USGS Director Charles Groat stated that detailed glacial geology information is vital for
understanding the hydrology, soils, and other environmental facets of the Great Lakes region. Also, many aspects of community life are dependent upon the surficial geology. This Earth-human interaction requires knowledge of the surface and near-surface processes (Groat, 1999). Interest in the surficial geology extends beyond the state geologic survey groups, as many agencies, community committees, and private companies have an urgent need for better information on the surficial geology (Hester, 1999).

It is foreseeable that Landsat TM images could contribute information and assist the Great Lakes Mapping Coalition with this endeavor. Currently, the glacial geology of Ohio has been mapped at 1:250,000 scale, with only a few select areas having been mapped at larger scales. Many geological applications involving surficial materials demand surficial geology maps with greater detail than currently available. The Landsat TM scenes have the potential to further subdivide the established glacial units, detect variations within units, and perhaps detect previously unnoticed materials and features.

**BACKGROUND**

The satellite remote sensing literature addressing glacial geology investigations is sparse. Glacial geologists have used aerial photography extensively for mapping glacial deposits and landforms; however, the application of satellite imagery for these same purposes has been limited. In the infancy of satellite remote sensing, glacial geologists utilized Landsat imagery in their studies, but they concluded that imagery was ineffective without detailed knowledge of the regional glacial geology, and that aerial photography contributed more information (Elson, 1980). However, these early studies were based on visual interpretations of single bands of data. Elson (1980) and the research he cites only
looked at single bands with no image enhancement techniques, no true- or false-color composites, nor any other data analysis technique. Single spectral bands contain only a limited portion of the electromagnetic spectrum and they have poorer spatial resolution than aerial photographs. The reduced spectral and spatial resolution thus makes aerial photographs more useful than single bands of TM imagery. Moreover, these results curtailed interest in remote sensing for many glacial geologists (Elson, 1980).

Although the literature is limited, a few geologists have used satellite imagery for glacial geology studies. Clark (1997) suggests initially looking at single bands because some geologic features may be more apparent than on false-color composites. Day (1995) examined the distribution and form of drumlins and moraines in Nova Scotia, Canada using Landsat TM band 4. Landforms and till were delineated using a contrast stretch technique, soil moisture, and vegetation type for these features. This enhanced image correlated well with previously published surficial maps of the study area.

Many studies have not been successful in discriminating till types and end moraines (Clark, 1997). In fact, end moraines seldom are successfully detected on Landsat TM images (Elson, 1980). In areas of continental glaciation, the end moraine is often similar in composition to the surrounding ground moraine. Thus, the spectral responses of these landforms are similar due to the comparable composition. This commonality has led to the use of geobotanical approaches for discriminating glacial landforms (Punkari, 1982). Aber et al (1993) developed a band ratio false-color composite scheme for effectively displaying the geobotanical aspects of the land surface. Aber’s (1993) scheme used MSS imagery band 3, 4/2, 1/2 (red, green, blue, respectively). This method proved effective in identifying natural vegetation stands. In areas such as
north-central Ohio many of the natural vegetation stands are not present at the spatial resolution required for geobotanical analysis. Thus, the geologist must use whatever other information is available.

METHODS

The Landsat image, dated June 11, 1984, was first corrected for atmospheric effects. Several dark objects (such as reservoirs and lakes) occur in the image suggesting a minimum histogram value of zero for most bands. An examination of the histograms and statistics for the individual bands revealed an offset from zero, probably indicating the presence of water vapor (haze) in the atmosphere. This atmospheric effect was reduced using the histogram adjustment method described by Jensen (1996).

Next, the image was geometrically rectified using a mosaic of nine USGS 7.5 minute (1:24,000) hydrography DLGs with the reference projection (UTM zone 17). The image was corrected using 48 GCPs with a total control point error of ± 1.2927 pixels and a total check point error of ± 0.8579 pixels. The image was resampled using nearest neighbor interpolation to retain the radiometry, and the resampled image was overlain with the stream network mosaic to verify geometric conformity.

Several band ratios were derived from the ratio selections in ERDAS Imagine 8.3 and by modifying the Normalized Difference Vegetation Index (NDVI) ratio model. These ratios were combined with the original bands into a single file for creating various false-color composites. A (7,7/1,4/5) composite permitted visual discrimination of the major glacial units of the region (lake deposits, beach ridges, and till). A principal component analysis was performed on the rectified image using six of the TM bands
(thermal band was deleted from the image). The resulting (PCA4, PCA3, PCA2) false-color composite displayed some subtleties and differences that were concealed in the traditional false-color composite and some of the ratio images.

The Quaternary map of Toledo (1:250,000) was reprojected from Albers Conical Equal Area to UTM zone 17. The Quaternary map was cropped to the boundaries of the TM image and then overlain on the enhanced images for comparison of the spectral characteristics with the known glacial units. Maps were created from the integrated data to illustrate the relationship between the glacial geology and the spectral characteristics of the image.

RESULTS AND DISCUSSION

The glacial geology of the study area consists mostly of till and lake deposits (Figure 5.1). The southern part of the image is end moraine (M4 on Figure 5.1), and ground moraine (G4 on Figure 5.1) is present immediately north of the end moraine. Both the end and ground moraines are composed of a clayey till. The northern section of the study area is characterized by lake deposits of sand (L.S on Figure 5.1), silt (L.L on Figure 5.1), and clay (L.C on Figure 5.1), and with lake-planed moraine (L.4 on Figure 5.1). Lake-planed moraine is ground moraine that was flattened, or planed, by waves from glacial lakes. Due to the presence of the lake, the lake-planed moraine unit has localized areas of sand, silt, or clay on the surface (Pavey and Goldthwait, 1993). The beach sand (B on Figure 5.1) corresponds to beach ridges formed from these glacial lakes. There are three prominent beach ridges oriented northeast-southwest, and there are some discontinuous beaches in the northeast section of the map. The southernmost
Holocene (Recent) 10 ka to present
  w water (The circular water feature is the Bellevue Reservoir)
  a alluvium

Late Wisconsinan; water-deposited units
  B beach ridges
  LS lacustrine sand
  LL lacustrine silt
  LC lacustrine clay

Late Wisconsinan, Late Woodfordian; ice-deposited units - Clayey till (Hiram)
  G4 ground moraine
  L4 lake-planed moraine
  M4 end moraine

Figure 5.1 Quaternary geology of north-central Ohio. Modified from the Toledo 1:250,000 sheet (Pavey and Goldthwait, 1993).
strandline was formed by glacial Lake Maumee, the beach immediately north was formed by glacial Lake Whittlesey, and the northermost beach ridge was constructed by glacial Lake Warren (Forsyth, 1959).

The (7,4,1) false-color composite (Figure 5.2) was used because the geologic information is contained in these bands. Band 7 is a clay absorption band (Ruiz-Armenta and Prol-Ledesma, 1998), and band 4 can be used for detecting soil moisture (Lillesand and Kiefer, 1994). The clay content is important as the till is clay rich, and glacial landforms have particular soil moisture and drainage characteristics. When overlain with the Quaternary map, the (7,4,1) composite (Figure 5.3) illustrates that the lake sediments can be spectrally distinguished from the till. The lacustrine sediments in the northwest corner of the image were visually different from the till in the south. These lacustrine sediments were displayed as blue in color whereas the till was reddish. This coloration supports the initial concept that the northwest corner is clay-rich since there is less red color in the area, indicating absorption in band 7 and thus high clay content.

The area in the center of the image is more problematic. The city in the east is Bellevue (V on Figure 5.3) and the circular water structure at the far center-right is the Bellevue reservoir. The city to the west is Clyde (C on Figure 5.3). Deposits between the two cities are difficult to classify based solely on spectral response. According to the glacial map, this area is lake-planed moraine with some sand deposits. The lake-planed moraine is difficult to distinguish from lake sediments and till because lake-planed moraine has a similar composition to both lake deposits and till. Thus, these deposits have similar spectral responses.
Figure 5.2. Landsat TM (7,4,1) false-color composite of north-central Ohio.
Figure 5.3. Landsat TM (7,4,1) false-color composite with the overlain 1:250,000 scale Quaternary map. The cities Bellevue and Clyde are labeled V and C, respectively.
Another complication is the dark reddish area immediately east of Bellevue (Figure 5.3). This area does not correspond to any known glacial unit. Possibly, the TM sensor recorded a slight variation within the glacial cover. There often is variation within glacial deposits, but this variation does not necessarily warrant separation of a unique unit. Complicated glacial lake activity occurred east and north of Bellevue after the late Wisconsinan maximum glaciation (Leverett, 1902). The area is characterized by several small, discontinuous sections of beach ridges of the Lake Maumee II strandline that was overridden by the later Lake Maumee III beach (Forsyth, 1959). The glacial lake processes that occurred in this area may have led to variation in organic matter content, drainage, and slight mineralogical changes in the glacial unit. This area corresponds to a soil boundary between the Bennington silt loam and Pewamo silty clay loam (Soil Survey, Erie County, Ohio, 1971). Both soils formed on glacial till, however, the Pewamo soils have a higher organic matter content in the surface layer and are poorly drained. The authors suspect the Landsat sensor recorded this difference in soil organic matter, a hypothesis that is further supported by the agriculture of the area. Sugar beets are somewhat common and beets require a moderate to high amount of organic matter (John Lyon, pers. comm., 1999).

Figure 5.4, (7,5,1) composite, illustrates a much different representation of the glacial geology. As in Figure 5.2, the lake sediments in the northwest corner are blue in color whereas the till in the south is pinkish, indicating a higher clay content in the northwest corner. The area east of Bellevue is also dark toned in this image, but the contrast of this material with the surrounding ground moraine is less dramatic than in Figure 5.2. Bands 5 and 7 are useful for discriminating mineralogy and rock type
Figure 5.4. Landsat TM (7,5,1) false-color composite of north-central Ohio.
(Lillesand and Kiefer, 1994), and are important for the detection of hydroxyl-bearing minerals, such as clay (Crippen, 1989). These bands provide a better visual representation of the glacial geology for the study area due to the high clay content in the till and the presence of lake clays. The color scheme of the glacial deposits in Figure 5.4 ranges from light brown-brown to pink-purple to blue. The large color range of Figure 5.4 as compared to Figure 5.2 indicates a wider range of spectral information is contained in this image.

Specific units were discernable on the (7,5,1) composite when overlain with the glacial map (Figure 5.5). In the northwest corner, the lacustrine clays appear blue and the lacustrine silts as light blue. The lake-planed moraine appears as a light blue-brown. Although the spectral differences do not exactly correspond with the boundaries of the glacial units as mapped, the image provides a visual discrimination of the different lake sediments. This image also illustrates that the geologic boundaries are gradational, not abrupt. However, when mapping, the geologist must decide where the unit boundaries occur. This decision becomes more difficult with glacial geology (as compared to bedrock geology) due to the spatial- and time-transgressive nature of glacial units. Also noticeable was the difference in the appearance of the lake-planed moraine and lacustrine sand areas between the beach ridges near Clyde. Between the northern and middle beaches is lake-planed moraine. The lacustrine sand has a brown color and can be distinguished from the bluer-toned lake-planed moraine.

As in Figure 5.3, the end moraine could not be distinguished from ground moraine in Figure 5.4. Drainage characteristics were more apparent in Figure 5.3, but this did not provide information about the position of the end moraine. End moraines usually
Figure 5.5. Landsat TM (7,5,1) false-color composite with the overlain 1:250,000 scale Quaternary map. The cities Bellevue and Clyde are labeled V and C, respectively.
are hummocky; therefore, low areas may be wet or ponded. Also, streams tend to be positioned parallel and adjacent to end moraines. As an end moraine forms, the glacier is stagnant and the glacial debris is dropped out as the ice melts, forming a ridge. This meltwater then drains along the ice front between the ice and the moraine. However, in the image area, there is no clear drainage that would suggest the northern boundary for the end moraine. The lack of an apparent boundary between end and ground moraine was probably the result of the end moraine itself. The end moraine, the Defiance Moraine, is a low and broad ridge with gently rolling to rolling topography. The cross-sectional shape of an end moraine has a distal side (farthest from the ice front) that is steeper than the proximal side (adjacent to the ice front). The Defiance Moraine has a gentle proximal side, so gentle, in fact, that many glacial geologists have had great difficulty in determining the northern boundary. Additionally, as mapped, the northern (proximal) boundary of the moraine varies by as much as two miles (Mike Angle, pers. comm., 1999). Obviously, other forms of image enhancement and interpretation are needed to discriminate end moraine from ground moraine.

Band ratios are useful in determining mineralogy and lithology; thus band ratio composites were examined to determine if such images provide more information on glacial geology than traditional false-color composites. A band ratio combination of (7,7/1,4/5) as red, green, blue (Figure 5.6) provided more detail than the (7,5,1) composite (Figures 5.4 and 5.5). The (7,5,1) composite did not provide as much detail on the soil variation in bare fields of the till areas. The ratio image displayed differences between fields (probably an artifact of agricultural activities), in addition to variations within the fields. These variations produced a mottled appearance of the bare ground in
Figure 5.6. Landsat TM (7, 7/1, 4/5) false-color composite of north-central Ohio.
the till area, which is indicative of ground moraine and end morainal landscapes. On Figure 5.6, the till has an orange-green color with a mottled tone whereas the lake deposits are dark green-brown and uniform in tone. The ratio image provides a clearer discrimination between the till in the south and the lake deposits in the northwest than the (7,4,1) or (7,5,1) composites.

Another important difference of the ratio image is the variation in vegetation in this ratio image. The vegetation appears green with very little tonal variation on the (7,5,1) false-color composite (Figures 5.4 and 5.5). The ratio image, however, provides a greater detail of the vegetation. The vegetation located on lake deposits has a uniform blue color, as did the vegetation on the lake-planed moraine. The vegetation on the till has a lighter, mottled, blue tone. The different spectral responses of the vegetation of these areas indicate some difference in the vegetation, and knowledge of the agricultural practices and land uses that may differ between these units should be extremely useful in unit discrimination. This knowledge should also lead to more advanced techniques for image interpretation to indicate various types of glacial deposits. However, field checking determined that the crop types did not vary between the units, nor was there evidence for different agricultural practices. The agriculture of the entire image area is dominantly corn and soybeans with no-till practices.

The glacial map was overlain on the ratio image (Figure 5.7) which allowed for further delineation of the glacial geology. As mentioned, the lake-planed moraine has a spectral response similar to the till and lake deposits. The lake-planed moraine, till, and lake sediments have similar mineralogical compositions that are the basis for their spectral responses. The vegetation information present on the ratio image provides an
Figure 5.7. Landsat TM (7, 7/1, 4/5) false-color composite with the overlain 1:250,000 scale Quaternary map. The cities Bellevue and Clyde are labeled V and C, respectively.
additional technique, geobotany, to delineate the glacial geology. The blue color of the vegetation in the ratio image indicates that the spectral response is dominated by the band 4/5 ratio. Vegetation dominates the spectral response in band 4 because of the plant’s cell structure, and water content dominates band 5 (Lillesand and Kiefer, 1994; John Lyon, pers. comm., 1999). The high spectral response and uniform tone of the vegetation in the lake plain sediments indicate healthy vegetation with a high water content. The soils of this area contribute moisture and nutrients for the crops. The till plain-based vegetation, although healthy, has a mottled appearance revealing the heterogeneity in the till soils.

A principal component analysis was performed on the six bands of the georeferenced image (thermal band was deleted). The eigenvalues (Table 5.1) established that 88 percent of the image variance is contained in PCA1. False-color composites that included the PCA1 image did not provide additional information. However, a false-color composite of (PCA4, PCA3, PCA2) in red, green, blue, proved useful (Figure 5.8). The three northeast-southwest beach ridges were obvious, appearing light blue to white in color. North of the strandlines was another feature with a similar orientation and appearance as the beach ridges. This arcuate feature (outlined on Figure

<table>
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<th>Principal Component</th>
<th>Eigenvalue</th>
<th>% Variance</th>
</tr>
</thead>
<tbody>
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<tr>
<td>PC2</td>
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<td>10.170</td>
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<td>PC3</td>
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<td>1.323</td>
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<tr>
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<td>0.152</td>
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</tr>
<tr>
<td>PC6</td>
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Table 5.1. Eigenvalues and the percent variance contained in each principal component.
Figure 5.8. Landsat TM (PCA4, PCA3, PCA2) false-color composite of north-central Ohio.
5.8) parallels the beach ridges at the top of the image. This feature occurs along the boundary between the lacustrine silts and lake-planed moraine (Figure 5.9) in the center of the image and along the lacustrine silt and lacustrine sand boundary in the west.

Although there are no mapped beach ridges in this area, the striking resemblance of this feature to the strandlines prompted further study. The last glacial lake present in Ohio was Lake Lundy and it had three minor phases (Forsyth, 1959). The beaches associated with this glacial lake are discontinuous and obscure. Segments of these beaches occur at elevations of 640, 620, and 615 feet. After examining the topographic maps for the area, the arcuate feature occurs at an elevation of approximately 620 feet, the level of the Dana beach of Lake Lundy (Forsyth, 1959). However, there are no indications of a beach being present based on topographic analysis or aerial photography. The location of the feature was determined from the image and then field checked. Field checking verified the presence of some low knolls of sand, but the overall feature could not be recognized as a continuous beach based on topography and sand content. From the stack map (map depicting vertical and horizontal distributions of surficial materials) of the area, the surficial geology is a spotty sand less than ten feet thick (Pavey et al., 1999). If this feature is the Dana beach, the relief must be less than ten feet; the low topographic relief and spotty nature of the sediment is typical of the Lundy beaches.

The Landsat sensor has identified the feature as spectrally continuous although neither topographic maps nor aerial photography identify the feature as being continuous. However, the arcuate feature follows the boundary between the lacustrine silts and lake-planed moraine in the center of the image (Figure 5.9) and the lacustrine silts and lacustrine sand in the northwest. This position corresponds to a lacustrine-terrestrial
Figure 5.9. Landsat TM (PCA4, PCA3, PCA2) false-color composite overlain with the 1:250,000 scale Quaternary map. The cities Bellevue and Clyde are labeled V and C, respectively.
interface – a beach. The lack of topographic and grain size continuity indicates a more subtle characteristic of the feature, such as mineralogy. The feature is most apparent on PCA3 (Figure 5.10) and bands 5 and 7 contribute the most information to this principal component (Table 5.2). These TM bands are detectors of hydroxyl-bearing minerals, such as clay minerals (Crippen, 1989). The appearance of this arcuate feature in PCA3 may indicate a very subtle clay mineralogical difference from the surrounding sediments.

End moraine was not detected on the principal component image. The composition and spectral properties of the end and ground moraine differ so subtly that a more powerful image enhancement technique or different sensor is needed to detect the end moraine. Isachsen et al (1973) detected end moraines in New York by a change in land use patterns from the surrounding ground moraine. The low, broad nature of the end moraine does not suggest a change in land use or agricultural practices from that of the bounding ground moraine. Perhaps the end moraine would be perceptible on the image if the soil moisture conditions were different. For example, due to the hummocky terrain of end moraines, water tends to pool after a rainfall. If an image were acquired after a rainfall episode the ponded water could provide information about the presence of end moraine landforms.

<table>
<thead>
<tr>
<th>TM Band</th>
<th>PC1</th>
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<th>PC3</th>
<th>PC4</th>
<th>PC5</th>
<th>PC6</th>
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<td>0.11417536</td>
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<td>0.78244915</td>
<td>-0.17084220</td>
<td>0.04288334</td>
</tr>
</tbody>
</table>

Table 5.2. Eigenvectors for the principal component analysis.
Figure 5.10. Landsat TM PCA3 image of north-central Ohio. The arcuate feature appears as light-toned in the northwest corner.
CONCLUSIONS

For glacial geology mapping, a (7,7/1,4/5) ratio image and a (PCA4, PCA3, PCA2) composite provide the best areal delineation of various glacial units within the study area. The ratio image provides information regarding the spectral differences between the bare fields on the lake deposits versus bare fields on till. Variations in vegetation that are indicative of the underlying glacial geology also are manifest in the image. The principal component image also illustrates variations in spectral qualities of the bare fields on till, contrasted with the more uniform tones of the bare fields on lake sediments. The (PCA4, PCA3, PCA2) composite detected a feature that was spectrally similar to the beach ridges and paralleled previously mapped beaches, and the authors hypothesize that this feature is a remnant of glacial Lake Lundy.

Although the enhanced images correlate well to the glacial map, there are features on the image that are not found on published maps. The area between Clyde and Bellevue and immediately east of Bellevue exhibit spectral differences that do not correspond to known glacial geology. These areas are characterized by soils that form on glacial till but have a high content of organic matter. Perhaps the variation of the organic matter within the till unit can be observed on the satellite image. Landforms such as end moraines could not be detected on the Landsat images, but may be detected by radar or hyperspectral sensors. The ability to delineate end and ground moraine composed of the same till type would be quite beneficial to glacial geology.
REFERENCES CITED


Clark, C. D., 1997. Reconstructing the evolutionary dynamics of former ice sheets using multi-temporal evidence, remote sensing and GIS, Quaternary Science Reviews, 16 (9): 1067-1092.


CHAPTER 6

CONCLUSIONS

The purpose of this study was to integrate Landsat TM data with a digital glacial map to delineate the glacial geology of north-central Ohio. The June, 1984 image was subset to a small area for a detailed study. The image was radiometrically and geometrically corrected. Image enhancement techniques were performed and the image was integrated with the glacial geology map for verification of the spectral delineation of the glacial units. Discrepancies between the image and digital map were investigated through fieldwork, aerial photography, soils maps and county soil reports, and topographic maps.

This project proved the value of satellite remote sensing to interpreting continental glaciation. Histogram equalization of (5,4,3), (7,4,1), and (7,5,1) false-color composites provided delineation of the areal extent of the glacial geology. Lake sediments were distinguished from till based on the tonal characteristics of these deposits. Lake deposits often have a uniform composition that produces a uniform spectral tone. The till composition is heterogeneous, resulting in a mottled spectral tone on the false-color composites. Beach ridges were recognizable due to their characteristic linear pattern and the presence of roads along their crests. Also evident on the enhanced
false-color composites was variation within glacial units. Soils with high organic matter content in surface layer were readily distinguishable from soils with low to moderate organic matter content.

A histogram equalization of band 4 allowed for superior determination of drainage patterns over the other bands and the false-color composites. Drainage patterns are fundamental to the discrimination of glacial units. Deranged drainage was present in the southern part of the image, indicative of end and ground moraines. The integrated drainage system of the lake sediments in the northwest was apparent on this enhanced band.

Some units and landforms were not identified on the enhanced false-color composites. Lake-planed moraine was not recognized as a separate unit. Lake-planed moraine is compositionally similar to both till and lake sediments, and therefore is also spectrally similar. End moraine could not be distinguished from ground moraine. The till composition of the ground and end moraines is the same, thus, the spectral response is the same.

Ratio images provided additional information for the separation of the glacial units. A (7, 7/1, 4/5) ratio image provided detail of the spectral differences between bare fields on the lake deposits versus the till. The uniform tone of the lake deposits allowed for distinction from the mottled tone of the till. Also manifest on the ratio image were vegetation variations that were indicative of the underlying geology. The vegetation on the lake sediments and lake-planed moraine had strong spectral responses on the 4/5 layer and were uniform in tone, indicating nutrient-rich soils with high moisture contents.
Although the till vegetation also had a high spectral response on the 4/5 layer, the tone of the vegetation was mottled. This tone indicated heterogeneous soil conditions typical of till deposits.

A (PCA4, PCA3, PCA2) false-color composite allowed for detection of a feature that appears to be a beach from glacial Lake Lundy. Such a feature has not been mapped and is not evident on aerial photographs, topographic maps, or stack maps. This feature is most apparent on PCA3, which has a majority of data contribution from bands 5 and 7. These bands are hydroxyl-bearing mineral detectors and may indicate a mineralogical continuity defining this beach.

End moraine was not identified on any of the enhanced images. The till composition of the end and ground moraines is the same in the study area and resulted in similar spectral responses of these two features. Also, the Defiance Moraine is a low, broad ridge with inexact boundary definitions. The low topography of this end moraine does not require changes in agriculture or land use practices that are so useful in end moraine detection on satellite imagery. The ability to separate end and ground moraine of the same till composition would be beneficial to glacial mapping. Perhaps an advanced classification technique, such as a textural analysis, could accomplish this daunting task.

Although the Defiance Moraine could not be detected on the imagery, this study proves the importance of the satellite remote sensing to Quaternary studies. The major glacial units of till, lake sediments, lake-planed moraine, and beach ridges were recognized on the enhanced images. Several important observations include:

- Drainage features, an important tool in glacial geology, were determined on band 4.
• The ratio image provided geobotanical information for delineation of the glacial geology. The literature addressing geobotanical methods in glaciated terrain have focused on native vegetation stands. This study has shown that the underlying geology affects all vegetation, including crops. Further development and application of geobotanical methods in glaciated areas utilizing remote sensing data is needed.

• The principal component analysis detected a possible beach ridge of Lake Lundy. Experienced Quaternary geologists have not recognized this feature as a continuous feature in the field, nor has it been identified on aerial photographs, topographic maps, or stack maps. The appearance of this possible beach on PCA3 is indicative of a mineralogical continuity that has escaped previous detection.
APPENDIX A

LANDSAT-5 TM SATELLITE SPECIFICATIONS

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<thead>
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<th>Band</th>
<th>Wavelength</th>
<th></th>
</tr>
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<tr>
<td>1</td>
<td>0.45 - 0.52 μm</td>
<td>visible blue-green</td>
</tr>
<tr>
<td>2</td>
<td>0.52 - 0.60 μm</td>
<td>visible green</td>
</tr>
<tr>
<td>3</td>
<td>0.63 - 0.69 μm</td>
<td>visible red</td>
</tr>
<tr>
<td>4</td>
<td>0.76 - 0.90 μm</td>
<td>near infrared</td>
</tr>
<tr>
<td>5</td>
<td>1.55 - 1.75 μm</td>
<td>middle infrared</td>
</tr>
<tr>
<td>6</td>
<td>10.40 - 12.50 μm</td>
<td>thermal infrared</td>
</tr>
<tr>
<td>7</td>
<td>2.08 - 2.35 μm</td>
<td>middle infrared</td>
</tr>
</tbody>
</table>

**Orbit**
Sun-synchronous
705 km altitude
16 day repeat cycle

**Resolution**
Radiometric: $2^8$ (256)
Spatial: 30 m; 120 m thermal (band 6)

**Geological characteristics of specified bands**
Band 1: useful for water penetration; soil and vegetation discrimination; identification of forest types; identification of cultural features

Band 4: vegetation type, vigor, and biomass; water detection; soil moisture detection

Band 5: useful for detection of rock types, vegetative moisture, and soil moisture

Band 7: useful for rock and mineral types; vegetative moisture content
# APPENDIX B

## GROUND CONTROL POINTS DATA TABLE

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<th>X Input (file coord.)</th>
<th>Y Input (file coord.)</th>
<th>X Reference (meters)</th>
<th>Y Reference (meters)</th>
<th>Type of Point</th>
<th>X residual</th>
<th>Y residual</th>
<th>RMS error</th>
<th>Contribution</th>
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APPENDIX B (continued)

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Check point error: x: 0.4674  y: 0.7184  total: 0.8579

Control point error: x: 0.6321  y: 1.1276  total: 1.2927
APPENDIX C

TRUE-COLOR AND COLOR INFRARED IMAGES

Figure C.1. Landsat TM true-color composite of north-central Ohio. Bands 3,2,1 are displayed as red, green, blue, respectively.
Figure C.2. Landsat TM color infrared composite of north-central Ohio. Bands 4, 3, 2 are displayed as red, green, blue, respectively.
LIST OF REFERENCES


Ohio Department of Natural Resources, Division of Soil and Water Conservation, 1997. Soil regions of Ohio.


United States Census Bureau, 1990. State and county Quick Facts area map.

United States Geological Survey, 1995. County map of Ohio, 1:2,000,000 scale DLG.

