Subsurface Analysis of Late Illinoian Deglacial Sediments in East-Central Illinois, United States, and Its Implications for Hydrostratigraphy

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Earth Sciences

Waterloo, Ontario, Canada, 2011

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

During the Illinoian glaciation (approximately 180,000 to 125,000 years ago) glacial lobes advancing into Illinois deposited an extensive till sheet (i.e., the Vandalia Member till). However, very little is known about the retreat phase that followed this major ice advance. Erosional events and the heterogeneous sediments associated to the Illinoian deglaciation may also have important hydrogeologic implications. Specifically, the occurrence and emplacement of these heterogeneous deposits, informally referred to as the Glasford deglacial unit, into and overlying the Vandalia Member till, may impact the integrity of this extensive till aquitard, and possibly influence groundwater flow to the deeper and regionally important Mahomet aquifer. Thus, the purpose of this research is to improve knowledge of the heterogeneous character of the Glasford deglacial sediments and their three-dimensional (3-D) hydrostratigraphic architecture.

The methodology to study the Glasford deglacial unit relies on the detailed analysis of 7 continuous cores and interpretations of 4 geophysical profiles, which provide key stratigraphic control to estimate unit geometry and establish the vertical succession of facies assemblages in the unit. A 3-D geological model was created using gOcad®, a geomodelling software, across a 2642 km^2 study area and the deglacial unit having a subsurface volume domain of 5.70x10^9 m^3. Utilizing all available data sources including 38 continuous cores, 69 downhole geophysical logs, 799 driller's logs, and 4 near-surface geophysical profiles; triangulated surfaces were interpolated representing the top and bottom of the Glasford deglacial unit and key internal layers. These surfaces provided a framework for a 3-D cellular partition, where descretizing the model allowed for mapping of hydrofacies assemblages that represented mappable heterogeneities of coarse- and fine-grained sediment in the Glasford deglacial unit.

Results of the subsurface facies analysis led to the identification of three main facies types that form the Glasford deglacial unit: 1) massive, matrix-supported diamicton; 2) interstratified sand and gravel; and 3) fine-grained massive and/or bedded sediment. Using key seismic reflectors and interpretations based on near-surface seismic profiles as well as geologic logs from numerous boreholes, these facies were assigned to two features of possible regional extent: 1) a broad channelized erosion surface informally named the Champaign valley; and 2) an extensive tabular unit overlying the valley fill and extending across the entire study area. Grouping of facies into distinct facies assemblages was useful

to distinguish sediments that in-fill either the Champaign valley or compose the tabular unit. Major heterogeneities have been recognized in these features and mapped at regional scale represented by fine- and coarse-grained sediment assemblages that comprise 46% and 54% respectively of the Glasford deglacial unit volume. Laterally continuous coarse-grained sediment assemblages are primarily located in the Champaign valley and potentially represent local aquifers of limited but usefully productivity for east-central Illinois. These small aquifers are characterized by hydraulic conductivities ranging from $1.07x10^{-3}$ m/s to $1.78x10^{-6}$ m/s. Fine-grained sediment assemblages have an average hydraulic conductivity value of $4.38x10^{-8}$ m/s and thus may represent discontinuous aquitards impeding water flow. However, these fine-grained sediment assemblages cannot be considered homogeneous aquitards because of their textural variability and limited lateral continuity.

The geological model developed in this study contributes to better understanding the complex subsurface geology in east-central Illinois. Results of this study confirm the high degree of heterogeneity in the Glasford deglacial unit that includes features of glacial erosion, and these findings question, at least locally, the integrity of the underlying Vandalia Member till as a regional aquitard unit. Overall, the Glasford deglacial unit is a complex subsurface ice-marginal package of sediments, which challenges the aquifer-aquitard concept. It is argued herein that some ice-contact or ice-marginal sediments units may be laterally extensive as a whole, yet internally too heterogeneous to be mapped as an aquifer or aquitard at a regional scale. A new conceptual hydrostratigraphic layer, the hybrid layer (part-aquifer/ part-aquitard), is thus proposed to better describe these units. This new hybrid layer is meant to augment the traditional aquifer/aquitard concept representing hydrostratigraphic bodies that may not form laterally extensive aquifer or aquitard units. These hybrid layers may better represent conceptually the complex ice-marginal deposits that are found across east-central Illinois, and perhaps other similar areas affected by glacial lobe fluctuations during multiple glaciations.

Acknowledgements

This research was conducted partially with contract funds from the Illinois State Geological Survey (ISGS) and additional funds from the University of Waterloo. In kind support in the form of access to sediment cores and samples, data and databases, and office space was provided by the ISGS, the Illinois State Water Survey (ISWS), and the University of Illinois at Urbana-Champaign. Additional support was provided by the Canadian Water Network, the Canada Foundation for Innovation, and a scholarship received from Amec-Geomatrix Consultants, Inc. Guidance from Dr. Martin Ross and Dr. Andrew Stumpf (ISGS and adjunct professor at the University of Waterloo) helped with the interpretation of data and essential review of the thesis is gratefully acknowledged. Lastly, I would like to thank the other members of my thesis committee: Dr. Paul Karrow and Dr. David Rudolph.

Dedication

This thesis is dedicated to my parents who have supported me from the beginning of my studies, and my Earth Science friends, especially Ryan and the ESC 203 ladies: Cassia, Ulanna, and Michelle.

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Preface

This research was a collaborative effort between the Illinois State Geological Survey (ISGS), the Illinois State Water Survey (ISWS), and the University of Waterloo. This multi-year project was funded under a contract, "Improving the Groundwater Flow Model of the Mahomet Aquifer including Geological Mapping and Geophysical Exploration of Champaign County," between the Illinois-American Water Company (IAWC), ISGS, and ISWS. Research undertaken by the author fulfilled the requirements of a subcontract between the ISGS and the University of Waterloo in 2009-2010. Additional funding was provided from the ISGS for the period of 2010-2011 under a separate contract. During this period, the ISGS received additional funding from the United States Geological Survey through the National Cooperative Geologic Mapping Program (STATEMAP) to complete a surficial geology map of a USGS 7.5-minute quadrangle in east-central Illinois. The research completed by the author also fulfilled requirements of this second subcontract between the ISGS and the University of Waterloo.

The research assisted the ISGS and ISWS in better understanding the geological, geophysical, and hydrogeological characteristics of the subsurface deposits in Champaign County and adjacent areas. Efforts to map the geology and groundwater flow patterns of the Mahomet and overlying aquifers have been a focus of many past and ongoing studies by the ISGS and ISWS. The data collected during this most recent study improved the geological framework of Quaternary deposits in this part of Illinois. The sediments that compose these deposits strongly influence recharge to, and discharge from, the Mahomet aquifer and overlying aquifers in the region.

This thesis is an extension of the project undertaken by the ISGS and the ISWS in which sediments above the Mahomet aquifer in the Glasford Formation were examined to provide understanding of the geology and possible groundwater flow patterns in the subsurface. Consequently, data collected for the ISGS-ISWS project were further examined in this thesis. Many individuals at the ISGS collected and interpreted data that were provided to the author for further examination.

The most significant contributions to the thesis by the ISGS include:

- All the continuous core and samples are stored at the ISGS and associated analytical laboratory data (e.g., grain size, clay mineral composition, etc.). For further information describing the drilling process, core and sample collection, and laboratory analyses refer to Chapters 5 and 10 in Stumpf and Dey (in press).

- Access to archived data collection during previous studies and databases developed by the ISGS for the current project. Geologic descriptions, interpretations, and models were provided to the author for further analysis and examination. See Chapters 2-4 in Stumpf and Dey (in press) for specific references to the data, databases, and models.

- Processed data, profiles, and interpretations from near-surface reflection seismic surveys covering approximately 8.8 km as well as processed seismic velocity profiles from selected boreholes. For further information on the methodologies used and the raw and processed data refer to Chapters 6-8 in Stumpf and Dey (in press).

- Processed data, profiles, and interpretations from Electrical Earth Resistivity surveys conducted covering approximately 10 km. For further information on the methodologies used and the raw and processed data refer to Chapter 7 in Stumpf and Dey (in press).

- Access to borehole geophysical log data (raw and processed data) collected for the ISGS-ISWS project and borehole data archived from previous investigations. Additional information on the tools used, the data collection, and results and interpretations from the logging are provided in Chapter 9 in Stumpf and Dey (in press).

- Access to georeferenced photo-mosaics, coordinates, and elevations from total station and GPS for the Higginsville section provided by Chris Stohr.

Chapter 1

Introduction

1.1 Quaternary Glaciations: Deposits and Uses

Continental ice volumes have varied throughout geological time. The Quaternary Period spans the last 2.6 million years of Earth's history (Gibbard et al. 2009) and is characterized by the high frequency waxing and wanning of continental ice sheets. During major glaciations, these ice sheets formed over northern regions and spread outward until they covered extensive parts of Canada, northern United States, northern Europe, and mountain ranges in southern Europe and Asia (Denton and Hughes 1981).

The Quaternary Period in northern North America is marked by glaciations and interglaciations (e.g., Johnson et al. 1997; Roy et al. 2004a). During the last glaciation, major ice lobes of the Laurentide Ice Sheet (LIS) advanced southward into Illinois, Michigan, Indiana, Ohio, and several other northern states (Figure 1.1) (Clark 1992). At the southern limits of these major ice lobes, glacial deposition was greater than erosion, causing thick sedimentary successions to accumulate over time with less stratigraphic hiatus than in other glaciated regions (Hansel and McKay 2010).

The glaciated terrain of the North American Interior Plains (Figure 1.1) is now one of the most economically important and populated areas in the world. As a result, knowledge of Quaternary glaciations, landforms, and the deposits left behind is extremely useful to ensure the sustainable and continued growth of regions underlain by glacial sediments. Understanding the formation and characteristics of thick glacial sediments is particularly important in these regions, as they contain significant groundwater resources; are a source of aggregates for construction and rich soils for agriculture; and provide areas of land for development, recreation, and wildlife habitats (Berg et al. 2000). However, conflicting human-activities in the near-surface glacial sediments lead to complex and critical resource-management issues including (Berg et al. 2000):

- Distribution of groundwater and surface water resources.
- Groundwater exploitation, and quality and quantity of water pumped.
- Agricultural run-off, erosion, and chemical use.
- Hazardous chemical-related production and storage facilities.

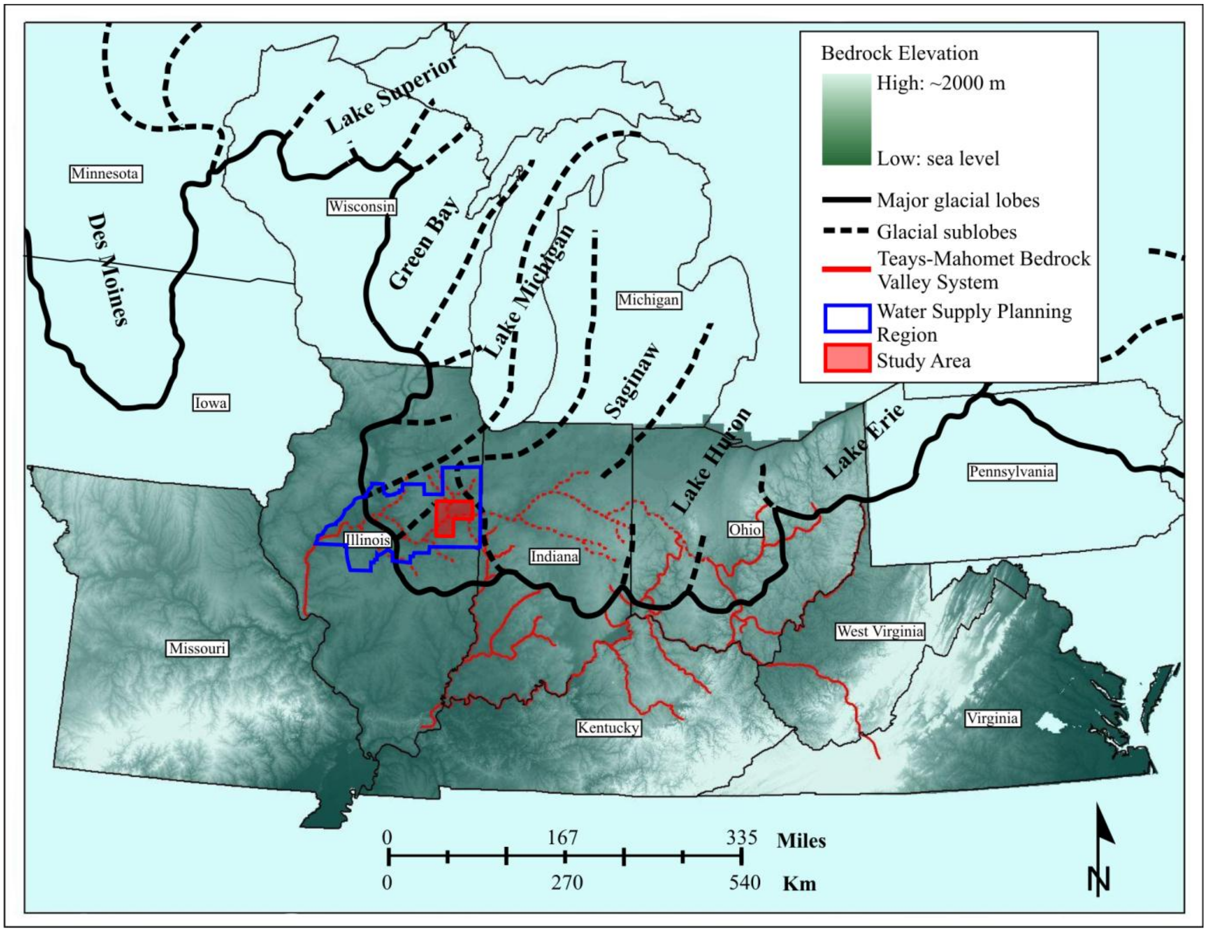

Figure 1.1: Glacial lobes active during the Wisconsinan. Flow paths of glaciers during the Illinoian and Pre-Illinoian are not known, but presumed to be similar to the configuration of the Lake Michigan Lobe during the Wisconsinan in the study area highlighted in red (Modified from Mickelson and Colgan 2003). Also shown is the largely buried bedrock valleys of the pre-glaciated landscape of the upper Midwestern U.S. (Modified from Stumpf and Dey in press), where the extensive Mahomet-Teays Bedrock Valley was carved by rivers active during the Quaternary Period and earlier. Thick glacial deposits are maintained in the map area and significant buried aquifers are preserved in portions of these bedrock valleys.

For decision-makers to resolve or better respond to these land-use and resource management problems, useable depictions of the land surface and underlying Quaternary age material through geological maps and three-dimensional (3-D) models are needed. Geological maps and models are particularly useful, in these situations, as a means to communicate and summarize spatial data about the earth's landscapes and sediments to government, industry, and the general public. Two-dimensional (2-D) maps have been the primary method to depict the characteristics, distribution, and thickness of surface and subsurface deposits (Jacobsen et al. 2011). However, 2-D maps provide limited information about the thick and complex nature of subsurface materials. A new generation of ‘maps’ in the form of 3-D geological models is needed to better represent the shallow subsurface, which because of its environmental and societal importance, is often referred to as the ‘critical zone’ (Brantley et al. 2005).

1.2 The Regional Quaternary Hydrostratigraphic Context and Research Problem

As a result of the numerous uses and applications that rely on the glaciated landscape and the resulting resource-management issues in the ‘critical zone’, there is a need for more subsurface analysis to understand Quaternary deposits and basins. Consequently, the geological surveys of Illinois, Indiana, Michigan, and Ohio have now contributed to the advancement of 3-D geological modeling as a part of the Great Lakes Mapping Coalition (Figure 1.2) (Berg et al. 2000). The Great Lakes region as a whole is home to 20% of the U.S. population, intensive agricultural practices, and major industrial centres, yet this area is not mapped in sufficient detail (McKay 2009). Although many of the pioneering efforts in mapping and glacial stratigraphic studies have come out of this area (e.g., Wayne 1963; Goldthwait et al. 1965; Willman and Frye 1970; Mickelson et al. 1984) the subsurface has not been described well enough to make informed decisions pertaining to management issues (Berg et al. 2000). However, with the formation of the Great Lakes Mapping Coalition, geologic information, resources, and capabilities are being shared to produce detailed 3-D surficial geological maps and derivative products, in several digital and consequently useable formats (Berg et al. 2000). Sharing the responsibility to map this highly complex area enables improved understanding of the stratigraphy and hydrostratigraphy of glacial sediments, and subsequently refines previous 2-D interpretations of glacial complexes.

The Illinois State Geological Survey (ISGS) is a member of the Great Lakes Mapping Coalition and has recently undertaken 3-D geological studies to model the Quaternary sediments from land surface to bedrock (e.g., Soller et al. 1999; Dey et al. 2004; Hansel 2005). Particular focus has been directed toward glacial deposits that host significant groundwater and economic resources. As a result, large bedrock valley systems have been targeted due to thick successions of permeable sand and gravel present at the bottom of these valleys (e.g., Mahomet-Teays, Figure 1.1; Mackinaw, Princeton, Troy, Rock River, Carthage, the Kaskaskia, and Cache Bedrock Valleys) (Larson and Herzog 2010).

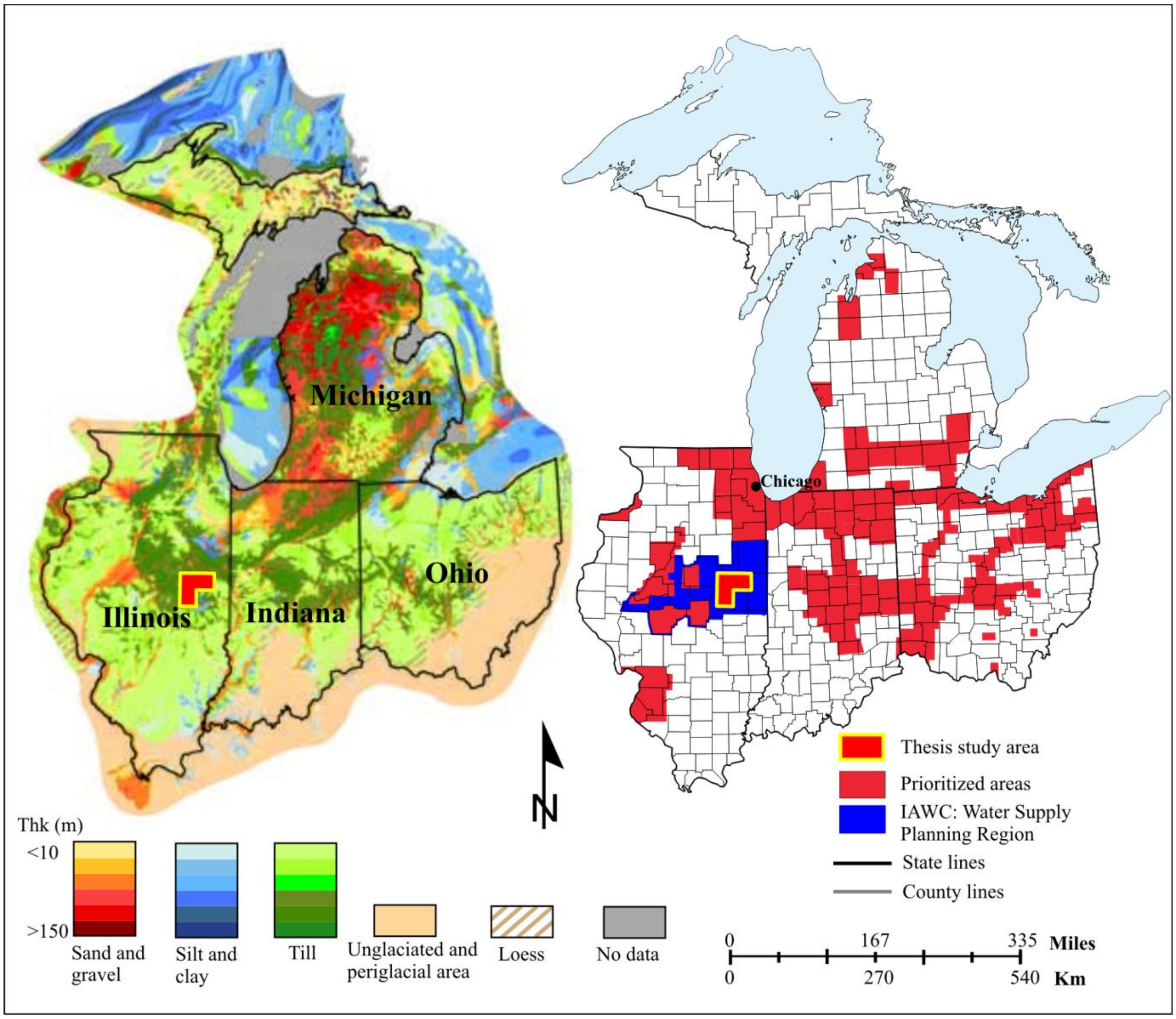

Figure 1.2: Map showing the states situated in the Great Lakes mapping region. Map on the left shows a summary of the thickness and character of major surficial deposits throughout the four states (darker colours indicate thicker deposits). Map on the right shows the Great Lakes Mapping Coalition's priority study areas for the creation of detailed 3-D geological maps of surficial materials. These study areas are targeted to address resource and hazard issues, transportation and industrial corridors, and environmentally sensitive zones. Many of the priority study areas are situated in areas of dense population (e.g., Chicago, Illinois) and where significant aquifers are located (i.e., along the Mahomet-Teays Bedrock Valley System, see Figure 1.1) (Modified from Central Great Lakes Geologic Mapping Coalition 2003).

A specific example in Illinois is the Mahomet Bedrock Valley (MBV), which contains sand and gravel composing the Mahomet aquifer, a significant water resource in central Illinois that partially fills the buried MBV. Other major sand and gravel aquifers in Illinois include the Sankoty aquifer, and aquifers within the Troy, Rock, and Princeton Bedrock Valleys (e.g., Berg et al. 1985; Vaiden et al. 2004). The Mahomet aquifer is considered an important water source to meet potential demands for water in the state (RWSPC 2009). As a result, significant research has been directed towards the MBV and the associated Mahomet aquifer (e.g., Horberg 1945; Kempton et al. 1991; Soller et al. 1999; Stumpf and Dey in press).

1.2.1 Mahomet Bedrock Valley in central Illinois

The MBV forms the western part of the Mahomet-Teays Bedrock Valley System (Figure 1.1) that extends from Illinois into Indiana and further east into Ohio and West Virginia, created during pre-glacial times as westward flowing water incised into Pennsylvanian shale, Mississippian limestone and dolostone with some shale, siltstone, and sandstone, and Silurian and Devonian limestone and dolostone (Kempton et al. 1991; Stumpf and Dey in press). The MBV shows no surface expression, and is buried beneath successive units of Quaternary deposits. This is a result of 90% of the landmass of Illinois being covered by different extents of ice through three different glacial stages (i.e., Pre-Illinoian, Illinoian, and Wisconsinan) (Figure 1.3 and Figure 1.4). In each glacial stage, lobes of ice flowed into Illinois depositing multiple glacial sequences. The sediments deposited by the glaciers, and the subsequent development of soils in surficial materials during warm interglacial periods, average approximately 91.5 m (300 ft) in thickness and deposits can reach thicknesses of 131 m (430 ft) in the MBV (Hansel and McKay 2010).

1.2.2 Mahomet Bedrock Valley Aquifer System

The Mahomet aquifer was formed as the MBV was repeatedly in-filled with sand and gravel and to a lesser extent water-laid silt (Figure 1.5) that formed during the Illinoian and Pre-Illinoian as glacial meltwater flowed westward along the MBV (Horberg 1946; Larson et al. 2003). The sand and gravel deposits throughout the MBV cover an area of approximately 5-10 km (3-6 miles) wide and is 15 to 60 m (50-200 ft) thick (Larson et al. 2003; Larson and Herzog 2010). The aquifer underlies 15 counties in Illinois (Figure 1.5), which supplies water to an estimated population of just over one million people (RWSPC 2009). The Mahomet aquifer is thought to be under confined conditions for most of this extent (Larson and Herzog 2010). Currently, groundwater withdrawals from the Mahomet aquifer are estimated to be 318 million l/day (litres per day) (84 million gallons per day or mgd) (Larson and Herzog 2010). These water withdrawals supply a variety of uses including: public water supply, self-supplied domestic, self-supplied commercial and industry, and agriculture and irrigation (RWSPC 2009).

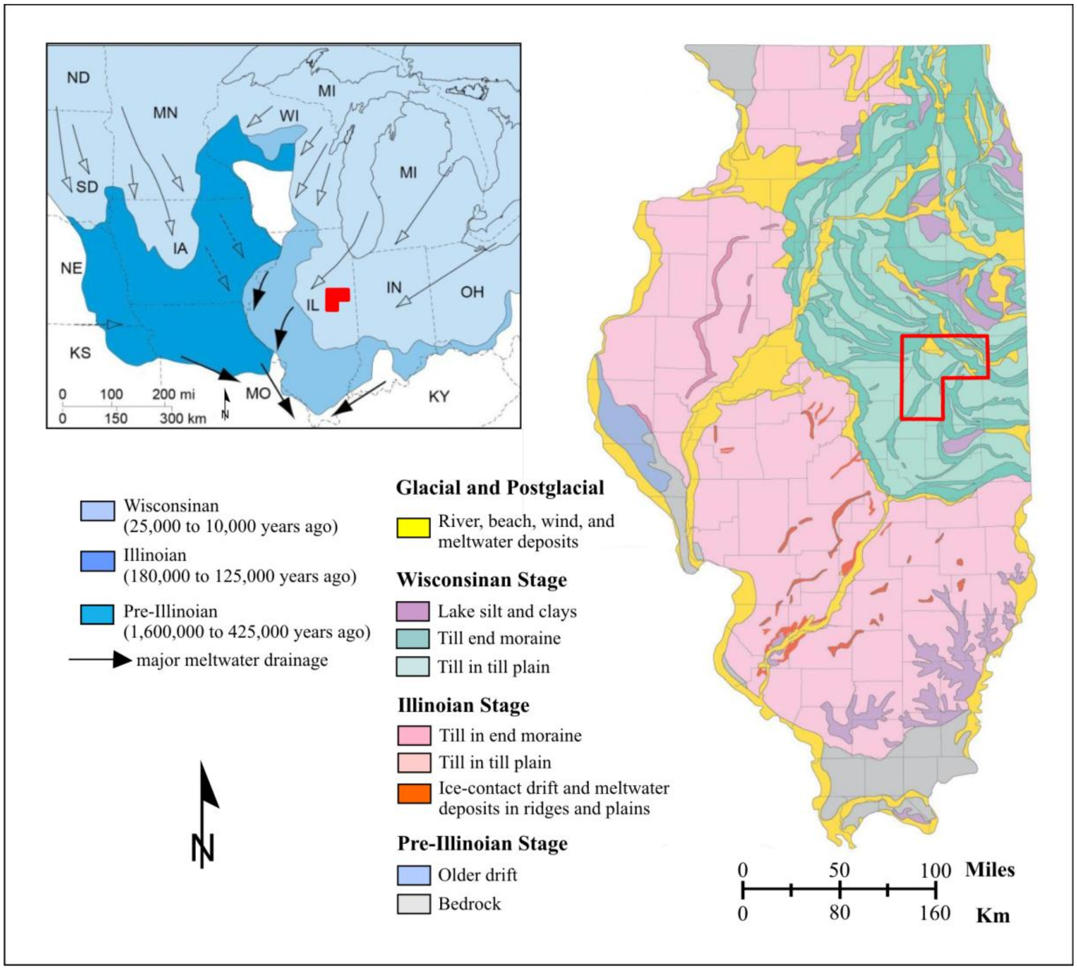

Figure 1.3: Quaternary deposits of Illinois during multiple glacial stages. The study area for this research, highlighted in red, has been impacted by at least three glacial stages, resulting in thick sequences of proglacial, subglacial, and ice-contact and/or ice-marginal glacial sediments (Modified from Hansel and McKay 2010).

Throughout the 15 counties the Mahomet aquifer underlies, groundwater recharge is supplied at varying rates. In general, groundwater recharge to the confined Mahomet aquifer is impeded by thick, relatively impermeable, layers of silt and clay (i.e., primarily till) as the Mahomet aquifer is a deeply buried unit (RWSPC 2009). The Banner Formation (Pre-Illinoian, Figure 1.4) and Glasford Formation (Illinoian, Figure 1.4) and overlying Wedron Group (Wisconsinan, Figure 1.4) are the three major glacial units overlying the MBV in the study area (Figure 1.5). These units are not constrained by the bedrock topography, and these glacial units are thought to provide sufficient confining conditions for the Mahomet aquifer (Herzog et al. 2003).

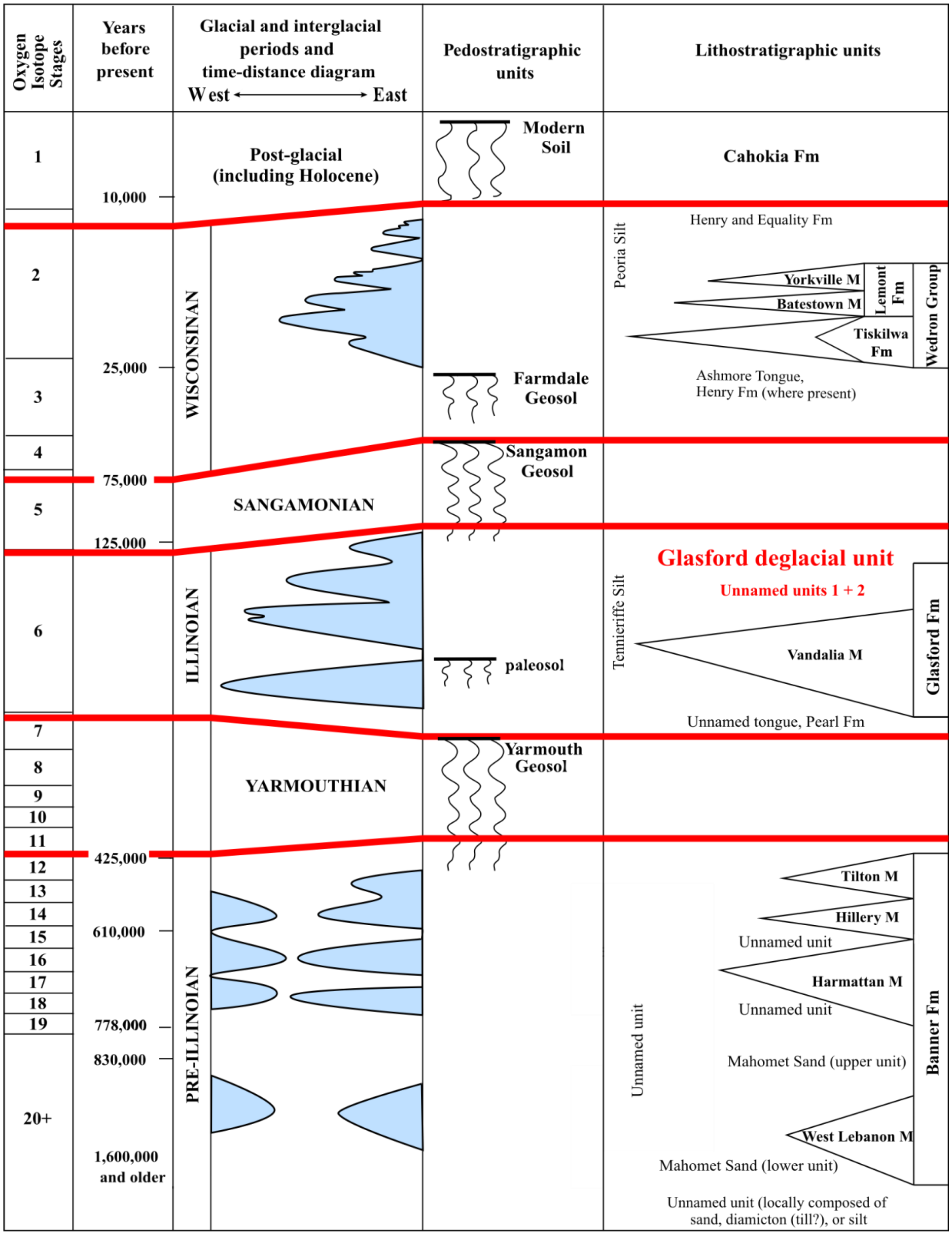

Figure 1.4: Quaternary stratigraphic framework for Illinois showing the major glacial and interglacial periods and the stratigraphic position of materials assigned to the lithostratigraphic units in east-central Illinois (Modified from Stumpf and Dey in press; Hansel and McKay 2010). In this study, the Glasford deglacial unit contains materials previously assigned to the Radnor Member of the Glasford Formation by Johnson et al. (1972).

In some cases, local hydraulic connections potentially exist between sand and gravel of the Mahomet aquifer and deposits of sand and gravel in overlying glacial units, especially where they are locally significant (Larson et al. 2003). These hydraulic connections are suggested by some descriptions from water-well records in east-central Illinois, due to the presence of overlying sand and gravel deposits and the discontinuity of till units in the Banner Formation (Larson et al. 2003). Discontinuous deposits of sand and gravel are present between the Banner Formation and overlying Glasford Formation, and between the two till units that have been traditionally described to comprise the Glasford Formation (Figure 1.4). Although, sand and gravel within the Glasford Formation have been described by previous researchers as typically thin and of limited areal extent, these deposits are considered to be locally significant sources of small community and domestic water supplies (Soller et al. 1999).

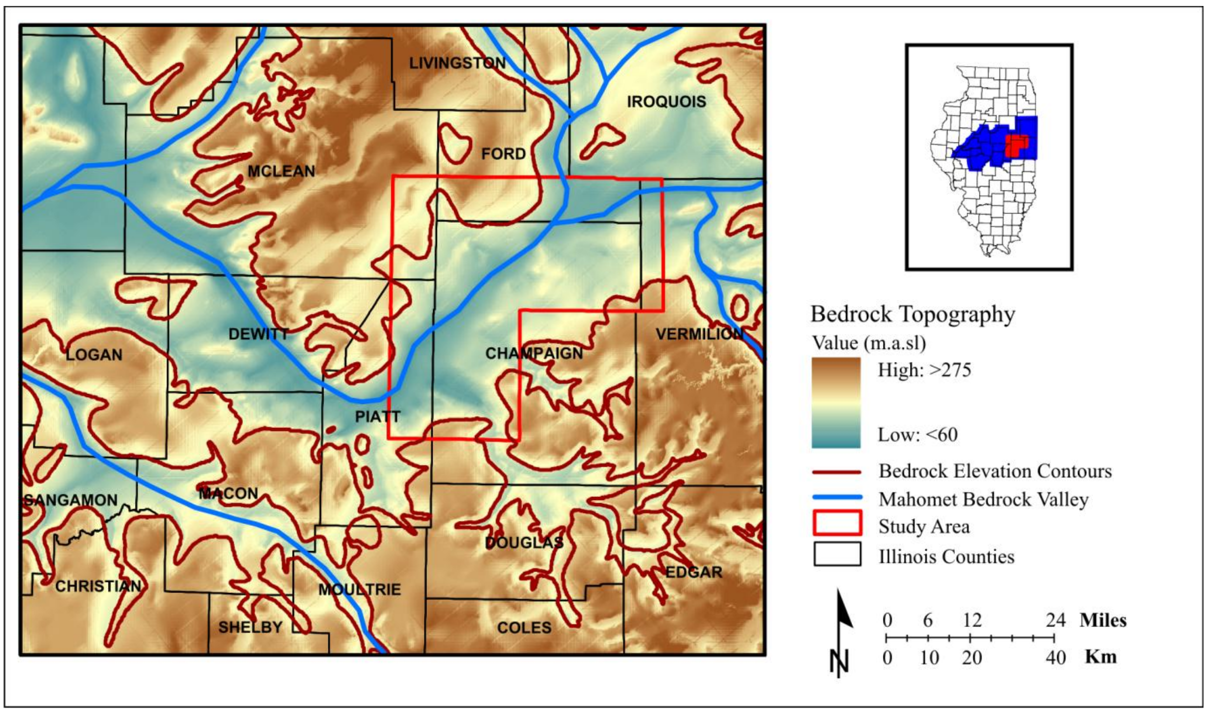

Figure 1.5: Bedrock topography of the MBV in a 15 county area in Illinois (blue filled area on inset map of Illinois). The red area on the inset map is the extent of the ISGS-ISWS project covering 30 townships (Modified from Herzog et al. 1994; National Atlas of the United States 2004).

1.2.3 Deglacial Sediment Assemblages of east-central Illinois

In addition to characterizing sediments composing the Mahomet aquifer, younger sediments in the overlying Glasford Formation, specifically in east-central Illinois (Figure 1.5), and potential hydraulic connections that exist between stratigraphic units are investigated because they can directly affect water quantity, quality, and availability in the Mahomet aquifer. Traditionally described Illinoian-age sediments of the Glasford Formation, in east-central Illinois, included subglacial tills with intervals of sand, gravel, and silt, primarily deposited as a result of the Lake Michigian lobe glaciation (e.g., Willman and Frye 1970). Previous understanding of the till stratigraphy of Illinoian deposits included two Illinoian-aged tills, the Vandalia and Radnor Members (Figure 1.4). The Vandalia Member till has been well studied in southern and east-central Illinois, and this stage of glaciation was marked by extensive stagnation during deglaciation. Deglaciation resulted in sedimentation on the Illinoian drift plain including: sand, sand and gravel, silt and partially sorted till-like material, which reflect ice-contact and/or ice-marginal deposits (Johnson 1976; Hansel and McKay 2010). However in east-central Illinois, the traditionally described geological framework did not include these deglacial sediments as a signficant stratigraphic unit. Instead, previous researchers described the upper part of the Glasford Formation, above the Vandalia Member till, as the Radnor Member till deposited during a Late Illinoian advance (Johnson 1976).

The Radnor Member till is described as somewhat variable in texture and commonly contains interbeds of sand and silt (Willman and Frye 1970). However, with the more recent study and collection of continuous cores, borehole geophysical logs, and near-surface geophysical data as a part of a study of the Mahomet aquifer by the ISGS in Champaign County (cf. Stumpf and Dey in press), more detailed information on the deposits was compiled, questioning the presence of the Radnor Member till. In addition, in some regions of the study area the Vandalia Member till was found to be locally incised, and in-filled with further heterogenous sediments of ice-contact and/or ice-marginal origins. This is a significant finding as it can potentially have a major impact on the regional geological framework, as the Vandalia Member till, was thought to be a significant confining bed for the Mahomet aquifer and this could in turn lead to signficant changes to the groundwater flow models that are currently being developed. Therefore, as a part of a case study in east-central Illinois, deglacial deposits found to overlie the Vandalia Member till, informally referred to as the Glasford deglacial unit (Figure 1.4), are assessed to provide insight on the heterogeneous deposits, their thickness, and extent, which will faciliate the formation of an updated geological framework for the study area. Consequently, this study of the Glasford deglacial unit is particularly important to 3-D mapping projects for east-central Illinois, as heterogeneities that exist in the large stratigraphic unit of the Glasford deglacial unit can strongly affect fluid flow in the subsurface, and can directly affect recharge to the underlying aquifers in the MBV.

1.3 Study Area

To meet growing water demands, a 15 county water supply planning region was developed in east-central Illinois (Figure 1.5), to assess and characterize water resources. The Mahomet aquifer is one of the two priority study areas in the 15 county region. It is a critical water resource for the state, but it needs to be better understood to ensure its sustainable management. As part of the ISGS-ISWS investigation of the Mahomet aquifer (cf. Stumpf and Dey in press) a 3-D geological model from land surface to bedrock was created to provide the most accurate and up-to-date geological framework for a groundwater flow model. Specifically, the geological modeling effort allowed stratigraphic correlations and general thickness and extent of described glacial sediments to be established in 3-D for inclusion into the groundwater flow model (Stumpf and Dey in press).

The original ISGS 3-D geological model of glacial materials from land surface to bedrock in east-central Illinois shows the Glasford deglacial unit as a single and homogeneous stratigraphic unit (cf. Stumpf and Dey in press). In this study, a new 3-D geological model has been created (Chapter 3) to include more detail of the Glasford deglacial unit (Chapter 2). Geological modeling of the Glasford deglacial unit is particularly important to characterize groundwater flow in the subsurface and improve the understanding of available groundwater resources in east-central Illinois. In addition, efforts to model heterogeneities within a stratigraphic unit are important as similar complex assemblages are prevalent throughout the glaciated regions of the North American Interior Plains.

1.4 Thesis Objectives

The main objectives of this thesis include:

- Update the geological framework of east-central Illinois by determining the physical character and properties of the sediments that form the Glasford deglacial unit. The characterization includes: studies and evaluations of the physical, geophysical, and mineralogical properties, and estimation of hydraulic conductivities.
- Development of the stratigraphic architecture of the Glasford deglacial unit along strategic transects.
  - Identify and map the lateral extent of windows in the underlying aquitard unit (i.e., the Vandalia Member till).
- Infer the depositional history of the Glasford deglacial unit.
  - Critical to the development of a robust conceptual model for stratigraphic correlation, facies transitions, etc.
- Model in 3-D the extent and thickness of facies assemblages in the Glasford deglacial unit.
  - Determine continuity between thin or discontinuous units, and identify facies assemblages that may be important for modeling groundwater flow.
  - Create derivative products (e.g., thickness maps).
- Compile all data into a project database.

These objectives were met to develop a comprehensive understanding of the Glasford deglacial unit (i.e., the distribution and vertical succession of sediments), and this is all essential to construct a consistent geological model that displays all deglacial sediment relationships in 3-D.

1.5 Methodology Overview

To refine the ISGS 3-D geological model and provide further detail in the 3-D Glasford model, a combination of descriptive techniques to characterize the unit as well as 3-D geological modeling was needed to satisfy the thesis objectives. The first two thesis objectives were accomplished through analysis of the geologic descriptions from seven continuous cores as well as investigation of the stratigraphic architecture of the unit through the interpretations provided by the ISGS (see Preface) of four geophysical profiles. Analysis of textural characteristics of sediments in examined cores, and vertical changes in facies types facilitated the subdivision of distinct facies assemblages, which form the Glasford deglacial unit. Subsequent, 3-D geological modeling of the complex and heterogeneous package of Illinoian deglacial sediments was undertaken to model the aquifer/aquitard geometries and internal heterogeneity in the Glasford deglacial unit. The methodology to study these features in 3-D relied upon the analyses of continuous cores and near-surface geophysics (outlined in Chapter 2) that provided key insights on unit geometry and facies changes both vertically and horizontally. Using all available datasets a Glasford database was created for the 3-D geological modeling including: new and archived continuous cores, engineering oil and gas borings, descriptions from water-wells, borehole geophysical logs, and near-surface seismic surveys. The Glasford database was developed for the geological modeling such that geological interpretations of all the data used to create the Glasford model are located in a common and accessible format.

Construction of the 3-D geological model of the Glasford deglacial unit was done in gOcad® (Paradigm™), a 3-D geomodelling program. Discrete triangulated surfaces were built by interpolating between points of standardized data representing the top of the Glasford deglacial unit as well as key internal layers. These surfaces were then used to build a stratigraphic grid, a SGRID object in gOcad, which is a sophisticated 3-D cellular partition of facies properties whose structure honours complex stratigraphic contact relationships (e.g., curvilinear, conformable, unconformable contacts). Analysis of internal heterogeneity for groundwater flow within the unit involved semi-automatically allocating cells within the SGRID as either coarse- or fine-grained material based on internal triangulated surfaces, and high-quality data in 3-D space. This modeling phase is important because it allows key control to be incorporated in the geological model, which is critical for investigating the impact of heterogeneity on hydraulic conditions.

1.6 Thesis Structure

The thesis is organized into four Chapters, two of which were prepared to facilitate future publication in scientific journals. Chapter 2 focuses on the description and interpretations of previously collected continuous cores, geophysical profiles, and borehole geophysical properties to provide new understanding of the character and origin of the subsurface facies of the Glasford deglacial unit, and to discuss the potential origin and significance of the unit. The examined continuous cores and geophysical surveys in Chapter 2, as well as data sources from numerous driller's logs from other boreholes, and logs of natural gamma radiation are integrated into the 3-D Glasford model. Chapter 3 highlights this geological modeling of the Glasford deglacial unit and provides some inferences on how the geological model can be used in hydrogeology applications. Finally, Chapter 4 summarizes the main insights on sediment characteristics and 3-D geometry of the Glasford deglacial unit, and the geological and hydrogeological implications this work may have in east-central Illinois.

Chapter 2

Subsurface analysis of Late Illinoian deglacial sediments in east-central Illinois, USA

Overview

During the Illinoian glaciation, which corresponds to marine isotope stage 6 (MIS 6), glacial lobes in Illinois advanced further south than during the last Wisconsinan glaciation, covering about 90% of the state, during which time a near continuous till sheet (Vandalia Member till) was deposited. However, very little is known about the retreat phase that followed this major ice advance. This is especially true for east-central Illinois, where the sediment land-systems of the Illinoian are completely buried by the younger Wisconsinan sediments. Here we are reporting on the character and distribution of subsurface deposits correlated to the deglacial phase of the Illinoian glaciation in east-central Illinois using data from seven continuous cores and interpretations of four geophysical profiles (i.e., seismic and resistivity surveys). These data provide evidence for the occurrence of a buried valley, informally named the Champaign valley, cut into the Vandalia Member till. This identified valley could potentially be part of a regional buried valley system. In the study area, the Champaign valley is overlain by a tabular unit, which is also part of the Illinoian deglacial sequence. The Glasford deglacial unit thus consists of two distinct subsurface architectural elements of possible regional extent: 1) the Champaign valley filled with three deglacial sediment assemblages (V1-V3), which is emplaced into the regional Vandalia Member till; and 2) an overlying tabular body consisting of three facies assemblages (A-C). Specifically, the Champaign valley is filled by interstratified, massive, and bedded sand (V1 and V3), as well as by bedded to massive silt and clay, and diamicton (V2). The tabular body that overlies the valley-fill consists of a highly heterogeneous package of interstratified sand (B) and diamicton (A and C), and discontinuous layers of fine-grained material (A and C). Overall, these heterogeneous complexes of the Glasford deglacial unit are interpreted to record a combination of ice-contact and/or ice-marginal deposition during the Illinoian deglaciation. This information provides a knowledge base for improving our understanding of the deglacial events of an earlier glaciation as well as major insights into the hydrostratigraphy, especially potential discontinuities in groundwater flow in the Vandalia till aquitard and on sediment heterogeneity within the Glasford deglacial unit.

Keywords: Illinoian deglaciation, buried valleys, near-surface seismic surveys, borehole geophysical logs, east-central Illinois

2.1 Introduction

In the glaciated portion of the North American Interior Plains, thick successions of sediments and associated landforms, record the advance and retreat of glacial lobes, as well as interglacial conditions. This terrestrial record, although often incomplete and fragmentary, provides major insights on the extent, timing, and the regional character of recent glaciations (e.g., Roy et al. 2004a; Karrow et al. 2000).

There is a long legacy of Quaternary stratigraphic studies in regions characterized by thick Quaternary successions (e.g., Leighton and Brophy 1961; Wayne 1963; Karrow 1974; Follmer et al. 1986; Johnson 1986). These thick glacial successions are prevalent in areas once situated at ice margins of major glacial lobes because deposition generally dominates over erosion near ice margins (Boulton 1996), leading to the relatively good preservation potential of successive glacial and interglacial sediments. Currently, the most well-studied terrestrial glacial landforms and deposits are from the last glaciation (Late Wisconsinan), as Wisconsinan sediments are expressed at the land surface and are relatively well-preserved. Although in some places, deposits and landforms of the penultimate glaciation (Illinoian) occur at the surface, such as in southern Illinois (Figure 2.1), where the last glaciation (Late Wisconsinan) was less extensive. However, these older deposits are much less understood and many lie buried in the subsurface.

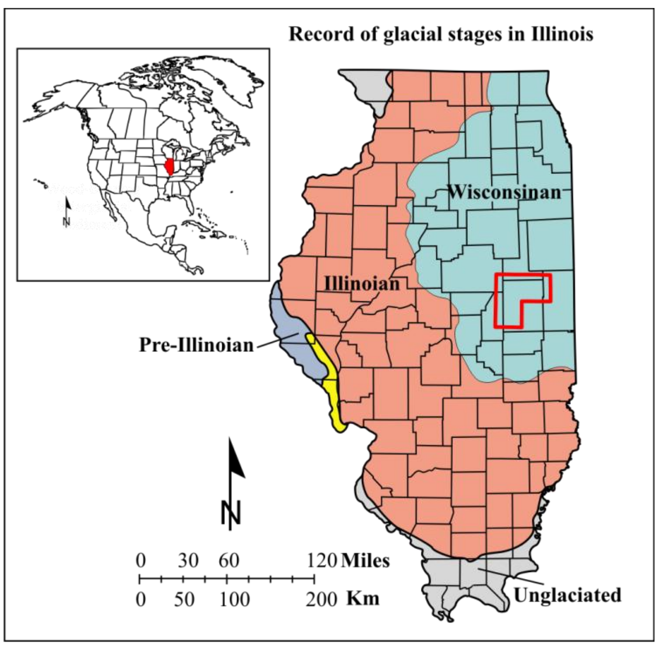

Figure 2.1: At land surface in Illinois, the Wisconsinan deposits outcrop and have been examined in detail. These deposits overlie older Illinoian and Pre-Illinoian sediments. In some areas these older sediments are at the land surface; however, in the study area (highlighted in red) subsurface examination of Illinoian deposits is needed as they are buried beneath a cover of Wisconsinan sediments (Modified from Hansel and Johnson 1996).

The study of the subsurface is challenging and it will generally be focused where subsurface mapping of unconsolidated Quaternary deposits is necessary to provide critical information for groundwater resources, engineering purposes, and aggregate needs. The combination of the societal need for subsurface information, and the variety of new techniques and processes available for surface and subsurface geological mapping (e.g., high resolution seismic and borehole geophysical tools, dating methods, digital mapping software and robust databases structures, etc.) provide an opportunity to gain new and important insights on Quaternary basin evolution and on the near-surface geological controls on groundwater systems.

In this paper, we examine subsurface architectural elements and associated sediments correlated to the Illinoian glaciation in east-central Illinois (Figure 2.1) with a focus on deglacial features to assess the implications of possible late Illinoian-age deglacial events. In addition, this study aims at improving our understanding of the subsurface stratigraphic geometry of Illinoian deposits in east-central Illinois.

2.1.1 Revising the Interpretation of the Illinoian Depositional Record

Newly acquired subsurface data collected in east-central Illinois as a part of a regional groundwater study of the deeply buried Mahomet Bedrock Valley (MBV) (Stumpf and Dey in press) has led to the re-examination of successive glacial tills that were deposited during the Illinoian as well as locally-thick deglacial deposits of late Illinoian-age (Figure 2.2). These data collected for a study of the MBV suggests that Illinoian-aged diamictons interpreted as till above the bedrock valley in the Glasford Formation are possibly associated with the deglaciation (Stumpf and Dey in press) following the regional advance of glaciers that deposited the continuous Vandalia Member till (Figure 2.2). This classification of Stumpf and Dey (in press) differs from previous interpretations of three diamicton units traditionally classified to till members of the Glasford Formation which included: locally the oldest Smithboro, Vandalia, and Radnor (Willman and Frye 1970). If the diamictons identified in the Glasford Formation are a result of deglaciation of the Vandalia Member till, a variety of ice-contact and/or ice-marginal processes would have also dominated the landscape. Thus, for this study a new deglaciation conceptual model is developed and the associated ice-contact and/or ice-marginal sediments have been grouped into the informally named Glasford deglacial unit (Figure 2.2).

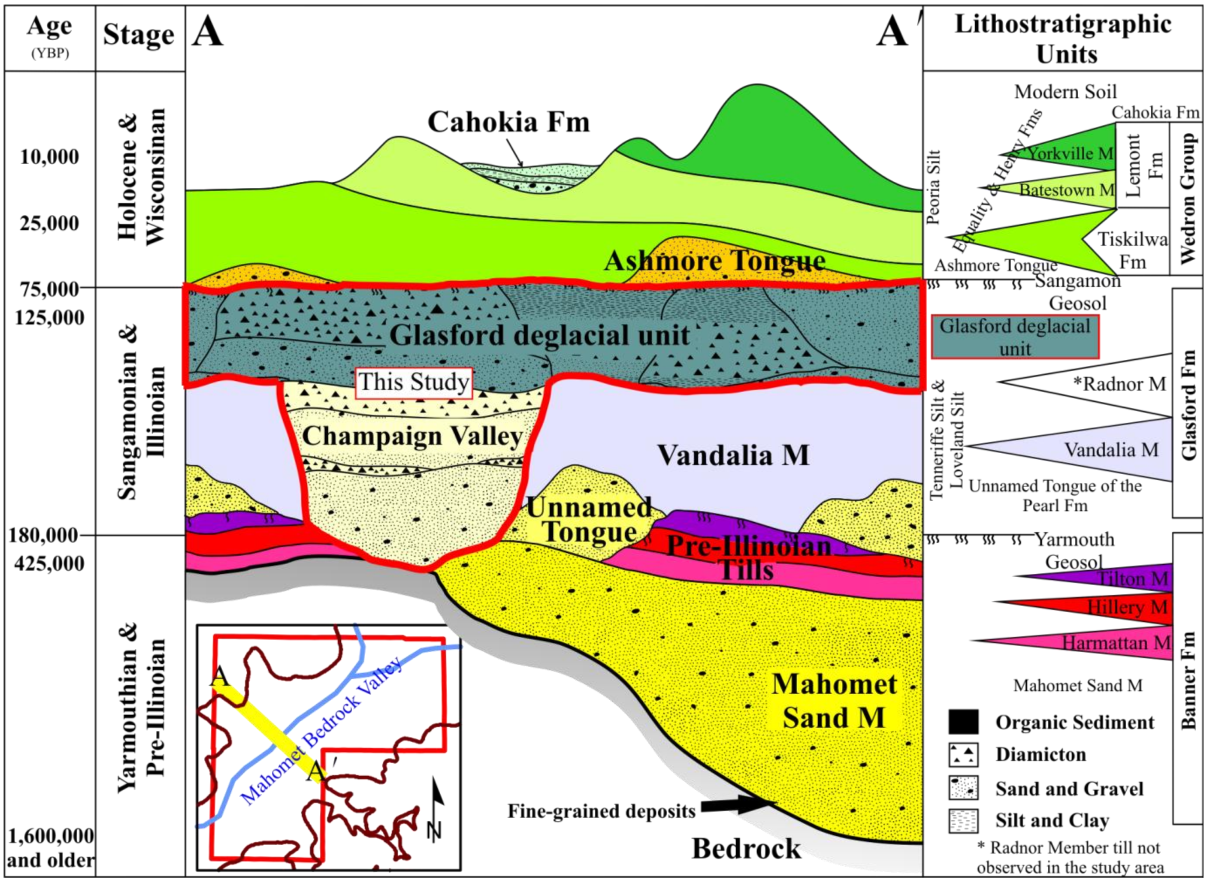

Figure 2.2: Cross-section A-A′ of the Quaternary stratigraphy in east-central Illinois from land surface to bedrock (see Figure 2.3 for study area location). Thick Wisconsinan deposits overlie the Glasford deglacial unit deposited during the Illinoian. The Glasford deglacial unit is a tabular unit, with a length and width much larger than its thickness, consisting of a heterogeneous mixture of sediments including: sand and gravel, diamicton, and silt and clay. Also shown is the associated Champaign valley that is overlain by the sediments of the tabular deglacial unit. Older sediments of the Glasford and Banner Formation were incised during valley formation and in some areas the valley terminates on bedrock. Sediments within the Champaign valley are quite variable, as significant sand and gravel deposits are located in the valley as well as diamictons and/or fine-grained units discontinuously preserved (Modified from Soller et al. 1999; Stumpf and Dey in press).

The deposits assigned to the Glasford deglacial unit contain sediment assemblages that are highly complex, laterally extensive, and contain sediment packages of varying composition. These packages of hetereogeneous sediments include significant deposits of sand and gravel, commonly present between diamicton units previously correlated to the Radnor and Vandalia members. However, on closer examination the diamicton classifed to the Radnor Member lack characteristics that are diagnostic of subglacial deposition (e.g., high bulk density and abundant striated iron-shaped clasts arranged in a fine-grained matrix), and they contain interstratified sediments displaying features that could potentially be associated with a wide range of glacial processes.

2.2 Study Area

The Glasford deglacial unit has been identified in an area of east-central Illinois, which covers parts of six counties that are mostly rural and contain many small communities and cities (Figure 2.3). To accurately characterize this unit, subsurface data were needed to provide key insights on the physical characteristics and geometry of the deglacial unit, as the older Illinoian landscape and associated sediments are buried in the subsurface and not widely exposed at the land surface (Figure 2.1). From these subsurface records it is apparent that the sediments forming the Glasford deglacial unit lie directly over the Illinoian-age Vandalia Member till, where the Radnor Member till was previously interpreted to have been positioned. The upper contact of the Glasford deglacial unit is identified by either: 1) the Sangamon Geosol, a paleosol associated with the last interglacial (i.e., Sangamonian, Figure 2.2) and is locally preserved separating the deposits of the Glasford Formation from the overlying Wisconsinan units (Figure 2.2); or 2) the lower contact of the well studied Wisconsinan sediments (Hansel and McKay 2010).

2.3 Methodology

The techniques used to characterize this unit include: 1) analysis of surface and borehole geophysical data; 2) detailed facies descriptions in core; and 3) grain size analyses of core subsamples. For this chapter, geophysical techniques (i.e., seismic reflection surveys, resistivity surveys, and borehole geophysical logging) were used to identify significant features in the deglacial unit. Seven continuous cores were examined to understand the sediment characteristics and physical properties of the sediments (borehole locations provided in Figure 2.3) within the major features outlined in the geophysical profiles. The combination of 2-D geophysical surveys and detailed vertical core descriptions aided in the construction of cross-sections (i.e., study areas 1-3, Figure 2.3). The cross-sections established material correlations along transects, thus improving the 3-D understanding of the Glasford deglacial unit.

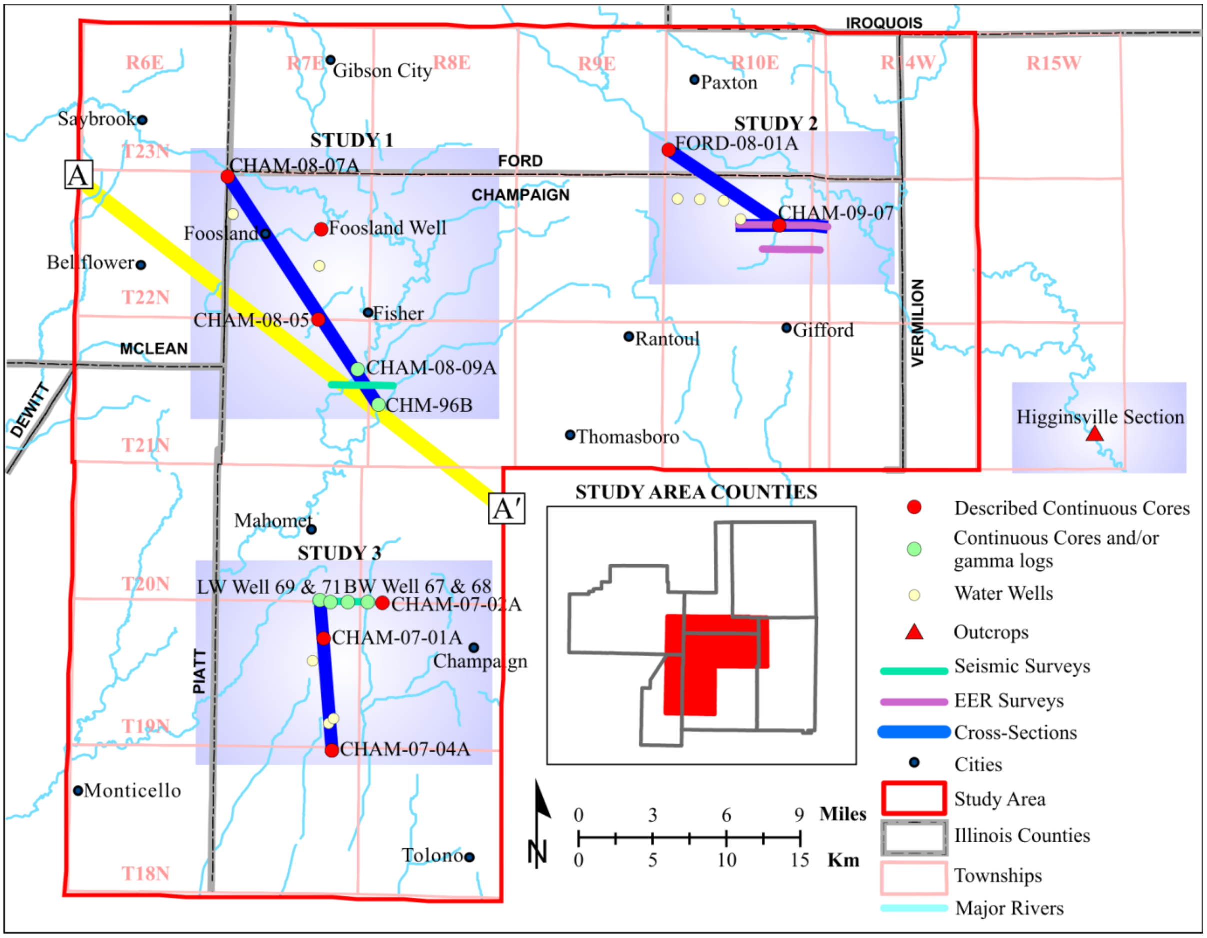

Figure 2.3: Map of the 30 township-wide study area in east-central Illinois, which encompasses 2642 km^2 (1642 mi^2). The 30 township-wide study area has been subdivided into focused study areas 1-3, which are highlighted in blue, and include data point locations used for cross-sections (Figure 2.9). These study areas are evenly spaced throughout the 30 township-wide study area to depict the various facies and features in the Glasford deglacial unit. Data points include: continuous cores, water-wells and associated sample sets (S.S), water and mineral test holes, borings with gamma logs, and one outcrop. Cross-section A-A′ is taken from Figure 2.2.

2.3.1 Seismic Reflection Data

Near-surface geophysical methods were used to provide important continuous high-quality data of the subsurface and understanding of the 3-D geometry of the sediments assigned to the Glasford deglacial unit (cf. Stumpf and Dey in press). Seismic reflection data were collected using a P-wave land-streamer (e.g., Pugin et al. 2004b). The geophysical surveys were collected along approximately 8.8 km (5.4 mi) of roadway in the study area (Figure 2.3). Facies seismic concepts were applied to the seismic lines by analyzing portions with differing aspects (e.g., amplitudes, frequencies and continuity of reflections) to identify large-scale trends within the Glasford deglacial unit (cf. Ismail et al. in press for complete methodology of seismic data collection and processing in the study area).

2.3.2 Electrical Earth Resistivity Data

Electrical Earth Resistivity data (EER) collected in the study area were also used for imaging the unconsolidated materials near the land surface (cf. Stumpf and Dey in press). EER is particularly useful in identifying textural changes in glacial sediments, which create a wide range of resistances to flow of an electrical current. When measured, EER data can be used to locate resistive gravel and sand, and conductive deposits of silt and clay (Larson 2000). In this study, the EER method was useful in determining the areal extent of sand and gravel bodies in the Glasford deglacial unit, and a rough estimate of the unit thickness could be calculated. Approximately 10 km (6.2 mi) of EER data were collected in the study area along two east-west transects. Using these techniques, geophysical interpretations were made to identify features within the deglacial deposits (cf. Larson et al. in press for complete methodology of EER data collection and processing in the study area).

2.3.3 Continuous Cores and Outcrop Sections

The combined description of sediments in cores and documentation of the sediment properties using grain size analyses aided in the subdivision of distinct facies within the features outlined in the geophysical profiles. Continuous cores for this study were acquired using the wireline mud-rotary drilling technique that utilized an inner barrel sampler for collecting the continuous core (cf. Stumpf and Dey in press). A total of seven boreholes (see Appendix A pg. 95 for intervals studied) out of thirty-eight continuous cores (see Appendix C pg. 134 for intervals studied) drilled by the ISGS (totaling 612 m or 2007 ft in length) were described for this study (Figure 2.3). The seven high-quality continuous cores examined for this study were chosen based on complete core recovery, high-quality natural radiation gamma geophysical logs, proximity to geophysical surveys, and the ability to cluster the selected continuous cores and geophysical profiles into three focused study areas for the creation of cross-sections. Each selected core averaged 87 m (285 ft) in total length (typically penetrating the bedrock), and 142 m (465 ft) of the total core contained sediments of the Glasford deglacial unit. Core recovery in the unit was generally very good allowing for detailed logging of core.

Recognition of the Glasford deglacial unit in these cores was based on well-constrained marker beds in the geological framework for east-central Illinois (Stumpf and Dey in press). The lower contact of the Glasford deglacial unit is readily recognized with high confidence in continuous cores as it is defined by the extensive, hard, and uniform Vandalia Member till (Figure 2.2). The upper contact of the Vandalia Member till is present at an approximate depth of 170 m (557 ft) in the study area, and it is easily recognized as a relatively sandy, grayish brown and compact loam till (Stumpf and Dey in press). Discontinuously throughout the study area, the formation of a large buried valley associated with the Glasford deglacial unit led to significant incisions into the Vandalia Member till. Areas where the buried valley exists, the lower contact of the deglacial unit is defined by underlying Illinoian and Pre-Illinoian sediments (Figure 2.2). The upper contact of the Glasford deglacial unit is also indentified in cores and is defined by the occurrence of the Sangamon Geosol, when preserved in glacial sequence and/or by the lower contact of the younger Wisconsinan sediments (Figure 2.2). Distinct Wisconsinan sediments include: 1) the sandy, pink-tan to reddish tan-brown Tiskilwa Formation till, generally described as the pink till (Willman and Frye 1970); and/or 2) sand and gravel of the Ashmore tongue (Stumpf and Dey in press) (Figure 2.2). In this study area, sediments between these two important and clear marker beds are assigned to the Glasford deglacial unit.

Detailed descriptions conducted by the author of the Glasford deglacial unit in continuous cores include physical descriptive characteristics such as: sediment colour, sediment and clast lithology, clast roundness, sorting, morphology and form of clasts (e.g., sphericity and roundness), sedimentary structures, and grain size. Facies were also described at an outcrop section located outside the study area (i.e., Higginsville section, location provided in Figure 2.3) to exhibit the lateral continuity and nature of the deglacial deposits (see Appendix A pg. 95 for interval studied). Building upon the facies description in cores and outcrop sections, facies exhibiting repeating patterns, gradational transitions, or other characteristics suggesting depositional relationships, were grouped into facies assemblages and correlated from borehole- to- borehole through cross-sections. Cross-sections were created using a customized tool for ESRI® ArcMap™ 9.3 developed at the ISGS (Carrell 2009). The cross-sections utilize continuous cores, borehole geophysical logs, near-surface seismic surveys, and EER surveys provided in this Chapter 2, as well as available samples, and geologic descriptions from logs of water-wells.

2.3.4 Grain Size Analysis

In each core, samples were taken for grain size analysis, which were selected to obtain quantitative textural information to compare with other data from continuous logs (e.g., natural gamma radiation and descriptive characteristics) and to characterize the vertical changes in physical properties of the Glasford deglacial unit. In this study, fifty-five grain size samples were taken for grain size analysis. Grain size distributions were generated using two different methodologies: sieving and laser techniques. Sieving techniques were used to characterize the coarse fraction. Samples were sieved using a Fritsch Analysette 3 Spartan shaker with five sieves (i.e., at intervals 0.6, 1, 2, 4, and 8 mm). The fraction that passed the last (0.6 mm) sieve was further analyzed with a Fritsch Analysette 22 MicroTec Plus, a laser diffractometer system with a 0.0008 mm to 2 mm grain size range. Resulting datasets from the sieve and laser approaches included: 1) weight percent data for sieving techniques; and 2) frequency data from the laser analysis. As a result, two different cumulative grain size curves were generated and a composite curve was produced by normalizing the laser cumulative curve with the weight of the passing fraction (<0.6 mm). Combination of the two grain size curves involved overlap of grain size classes between the sieve and laser analyses. This overlap of grain size classes was necessary when combining the differing methods, as discrepancies between the grain size classes outlined in the two methods may have caused some of the particles passing the 0.6 mm mesh to be analyzed as slightly coarser than 0.6 mm by the laser. Consequently, an average cumulative grain size curve was produced to combine the two differing datasets and grain size statistics for each sample were generated (see Appendix B pg. 132 for all grain size analyzes and Appendix D pg. 143 Table D.1 for grain size statistics).

2.3.5 Borehole Geophysical Logging

After drilling of boreholes, downhole natural gamma logs were taken, which provide a continuous estimate of texture and mineralogy in a borehole (e.g., Figure 2.7 A and B). Through combining core descriptions from the seven described continuous cores in this chapter and borehole geophysical logs, the thickness and variability of sediment packages were obtained. Instances where core recovery was incomplete, natural gamma logs were particularly useful to infer the lithology of missing sediments and to establish the position of important stratigraphic contacts. The gamma log measures the naturally emitted radioactive isotopes of potassium (K), uranium (U), and thorium (Th) in geologic materials and the gamma values indicate the relative abundance of these radioactive elements (predominantly from ^{40}K). Since gamma logs are continuous, they are particularly useful to identify trends in boreholes such as coarsening or fining-upward sequences. These elements tend to be more abundant in fine-grained materials (i.e., silt and clay) (Boyce and Eyles 2000), hence the use of gamma data as a proxy for grain size with lower gamma values corresponding to coarse-grained materials, and higher values corresponding to finer-grained materials. But, there are cases where radioactive elements are found to be locally-enriched in relatively coarse-grained sediments or where clasts of granite are present causing the natural gamma signal to be skewed. Therefore, it is important to use gamma logs in conjunction with core descriptions, mineralogical composition data, and grain size data whenever possible.

2.4 Results and Interpretations

Integration of subsurface data from geophysical profiles, continuous cores, and one outcrop, allowed for the detailed description of the geometry, sediment characteristics, and properties of the Glasford deglacial unit. Grouping of unique deglacial facies into facies assemblages, and the subsequent vertical and lateral representation of the assemblages in three cross-sections constructed from available datasets was fundamental to advance understanding of the highly-complex package of deglacial sediments.

2.4.1 Geophysical Profiles

Using key reflectors and interpretations based on near-surface seismic profiles provided by the ISGS (see preface), large-scale features of the Glasford deglacial unit were established. The Glasford deglacial unit is divided into two distinct features including: 1) a buried valley, informally named the Champaign valley; and 2) an overlying tabular body of sediments that exceeds the margins of the valley (e.g., cross-section B-B′, Figure 2.4).

2.4.1.1 Champaign valley

P-wave seismic reflection profiles show the cross-sectional outline of the Champaign valley along two transects (Figure 2.5). The valley is visible on the seismic profiles as an erosional surface cut into the underlying Illinoian and Pre-Illinoian sediments (Figure 2.5). The buried Champaign valley breaches the regionally extensive Vandalia Member till (cross-section B-B′, Figure 2.4 and Figure 2.5) and is such a large feature that it is regarded as one of the basic building blocks of the Glasford deglacial unit.

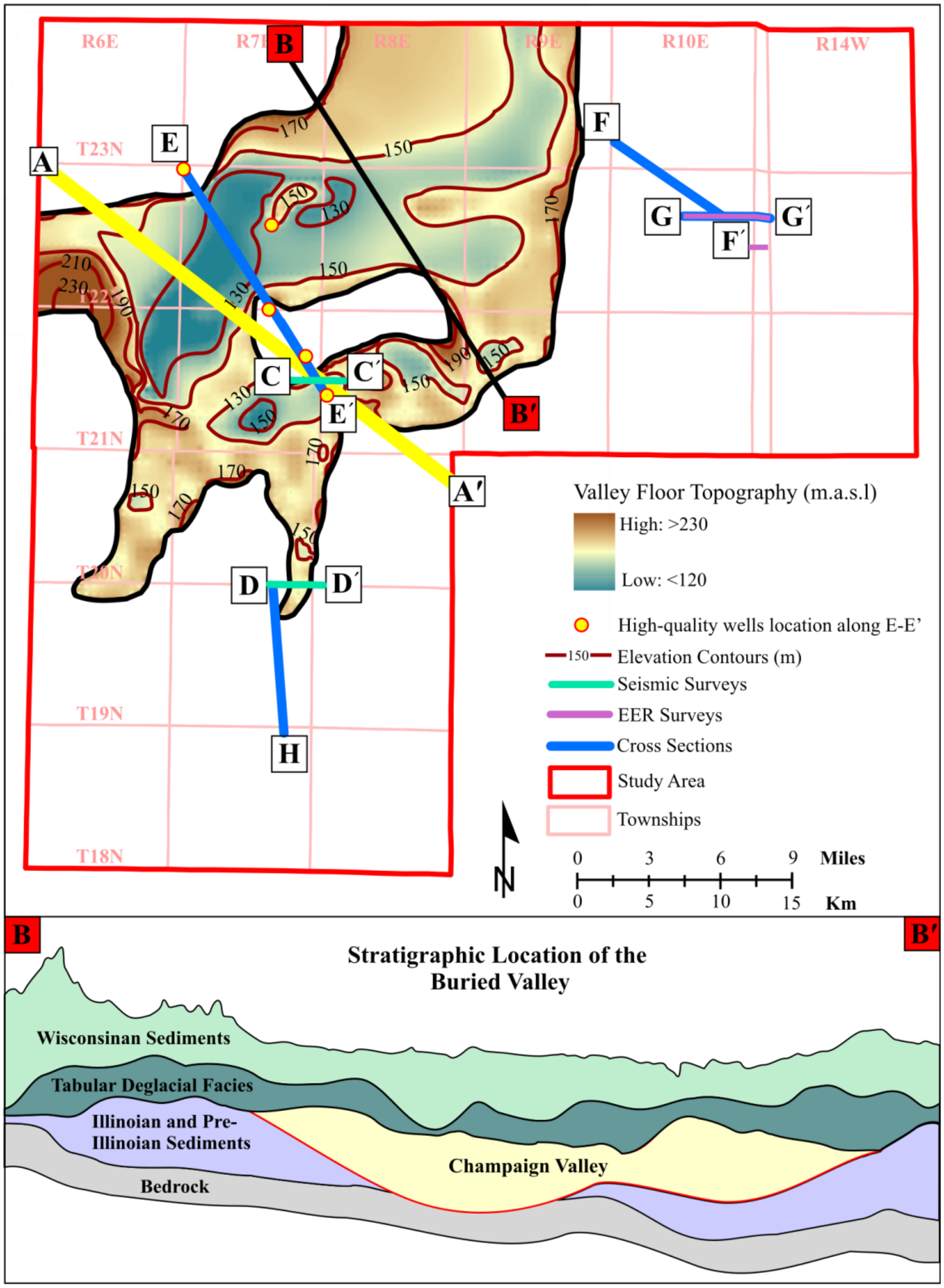

Figure 2.4: Cross-sections constructed across the Champaign valley in the study area and map showing the topography of the valley floor (contour interval = 20 m). Delineation of the Champaign valley is constrained by data from approximately 470 boreholes, including a limited number of continuous cores, borehole geophysical logs, descriptions of samples collected during the drilling of water-wells, geologic information recorded from the drilling of boreholes, and near-surface geophysical surveys (see Appendix B pg. 132 for all data sources used). Cross section B-B′ shows the geology across the Champaign valley in the described data sets.

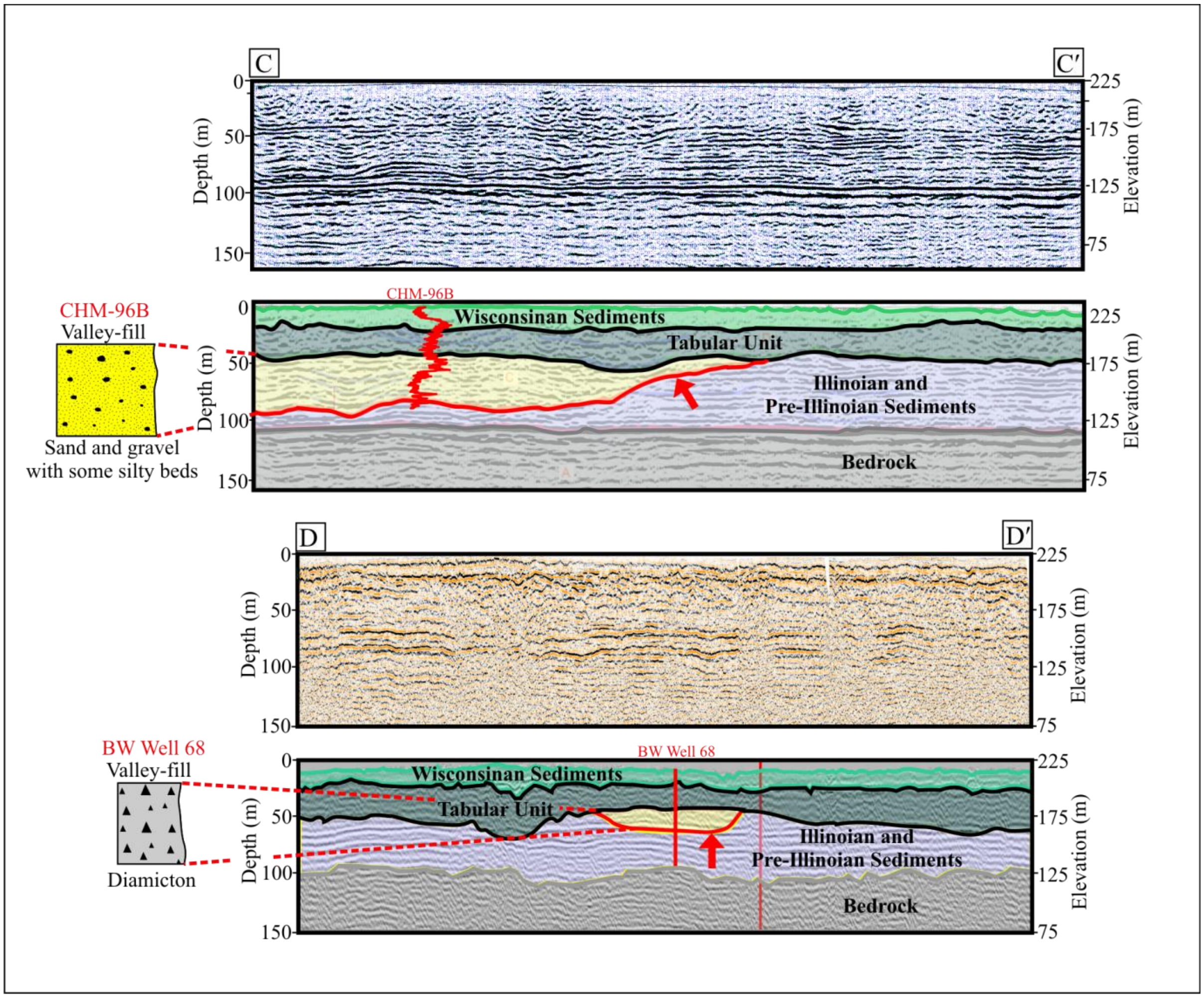

Figure 2.5: In cross-sections C-C′ and D-D′ (location provided in Figure 2.3 and Figure 2.4), the interpreted geology from the land surface to bedrock is shown on profiles of P-wave seismic reflection data (raw seismic data displayed above interpreted data). The strong flat reflectors near 100 m (328 ft) depth are interpreted as the bedrock surface. A series of reflectors above are truncated (indicated with arrows on the seismic profiles). This is interpreted as an erosional surface that forms the base of the broad Champaign valley (outlined in red). Another strong and continuous reflector is interpreted to mark the lower bounding contact of an extensive tabular body (indicated by the dark green). The geophysical data shown in cross-section C-C′ are from Pugin et al. (2004a). The P-wave seismic data shown in cross-section D-D′ were collected for a groundwater study of east-central Illinois (cf. Stumpf and Dey in press). The vertical exaggeration for these two cross-sections is 10X.

The Champaign valley extends across the study area and the valley clearly incises older glacial sediments. The boreholes that are situated within the valley margins are consistent with incision into the underlying Illinoian and Pre-Illinoian sediments (CHM-96B and BW Well 68, Figure 2.5). In some borings, borehole geophysical logs aided in identifying the Champaign valley. Overall, within the valley margins the uniform gamma signal that is indicative of the Vandalia Member till is missing, and further heterogeneous sediments are reflected by the borehole geophysical logs. These borehole geophysical logs and seismic profiles show that much of the glacial material the valley incises includes: underlying till members (i.e., Vandalia Member till and Pre-Illinoian tills) and to a lesser extent underlying sand and gravel (i.e., Unnamed tongues of the Pearl Formation). In place of these units, data collected from continuous cores, borehole geophysical logs, and geologic logs from water-wells in the Champaign valley, show that the valley is filled with interstratified sand and gravel (CHM-96B, Figure 2.5), fine-grained material, and diamictons (BW Well 68, Figure 2.5) (also see Foosland Well for valley fill, Figure 2.7 A). Valley-fill averages 30 m (100 ft) in thickness (Figure 2.4).

The total extent of Champaign valley is unknown; however, preliminary valley coverage in the study area has been identified (Figure 2.4 as a part of the ISGS 3-D geological model). The overall valley trends in a NE-SW orientation and a sediment island in the middle of the valley is aligned parallel to the valley walls. In some cases the valley has steep walls, and is broad with a maximum width of 7.4 km (4.6 mi). The valley floor topography is interpreted to show valley depths greatest towards the middle of the valley and shallower to the outer margins (interpretation of the Champaign valley floor topography as a part of the ISGS 3-D geological model, Figure 2.4). Maximum length of the valley was not determined in this study, as the valley extends outside of the study area; however, within the study area the valley has a maximum length of 13.9 km (8.6 mi).

2.4.1.2 Tabular Body of Sediments

The tabular body of deglacial sediments that overlies the Champaign valley in the Glasford deglacial unit is thought to be widespread and continuous throughout the study area (e.g., cross-section B-B′, Figure 2.4). The lower contact of the tabular body of sediments is shown on the P-wave seismic profile as a flat reflector overlying the Champaign valley or the underlying Illinoian and Pre-Illinoian sediments at an average depth of 55 m (180 ft) (Figure 2.5). The upper contact of the tabular body marks the top of the Glasford deglacial unit and is also visible on the P-wave seismic profiles as another strong and flat reflector at an average depth of 26 m (85 ft) (Figure 2.5). However, the extent of the tabular unit is largely based on geologic logs from boreholes and geophysical logs. In borehole geophysical logs the upper contact of the tabular unit was typically identified by a shift from uniformly high natural radiation gamma signals (i.e., high CPS) in the Wisconsinan tills (CHAM-08-09A, Figure 2.5) to a fluctuating gamma signal in the Glasford deglacial unit, denoting the presence of a interlayered coarse- to fine-grained package of materials (CHAM-08-09A, Figure 2.5). The lower contact again showed high natural radiation gamma signals, associated with the thick uniform Vandalia Member till or the presence of silt and clay (CHAM-08-09A, Figure 2.5). In addition, in many of the continuous cores and geologic logs from water-wells the lower contact of the tabular body is defined by the top of the valley-fill, which approximately in-fills the Champaign valley architecture (see section 2.5 for facies assemblages V1-V3 within the valley margins) or by the upper contact of the Vandalia Member till when situated outside the valley margins (cross-section A-A′, Figure 2.2).

2.4.2 Facies Descriptions

Examination of boreholes located within the Champaign valley or tabular body led to the identification of three main facies that were determined based on material types. The facies include: 1) massive, matrix-supported diamicton; 2) interstratified sand and gravel; and 3) fine-grained massive and/or bedded sediment. Due to subaerial weathering of older glacial surfaces (Figure 2.6 A) under interglacial conditions following the Illinoian glaciation, the top sequence of these facies locally can be constrained by the presence of a paleosol.

Table 2.1. Main facies types and characteristics.

Facies Type	Characteristics	Total Thickness
Diamicton	Poorly-sorted, massive, predominantly silt loam in texture.	~15-25 m
Sand and gravel	Poorly-sorted coarse sand with gravel and pebbles to massive or bedded fine sand.	~20-40 m
Silt and clay	Massive or laminated clay or silt with minor amounts of sand.	Thin; unit thickness <3 m

2.4.2.1 Diamictons

Poorly-sorted, massive, unconsolidated sediment containing a mixture of sand, silt, clay, gravel, and pebbles is referred to as diamicton (Dreimanis 1989). The multiple diamictons identified in the cores contain at least 50% silt and clay, and predominantly have a silt loam texture (Table 2.1 and Figure 2.6 B). The diamicton ranges from grayish-brown to dark-grayish brown (10YR 5/2) in colour. General characteristics of the diamicton units include: 1) an upper interval with no discernible internal structure; and 2) a lower interval of the sequence with lenses of sand and gravel and bounding contacts with underlying material that vary in their character (e.g., facies assemblage A in CHAM-08-7A and CHAM-08-05, Figure 2.7 A). Approximately 5-20% of clasts are preserved in the silt loam diamicton. Lithologies include: predominantly chert, and to a lesser extent dolostone, limestone, siltstone, sandstone, and few shield lithologies (e.g., igneous or metamorphic rocks). Clasts are predominantly angular to sub-rounded and clast size ranges from small (5-8 mm) to very large (35-60 mm). In rare cases, cobbles are larger in diameter than the size of the core (as indicated by Bcm in CHAM-07-01A, Figure 2.7 B).

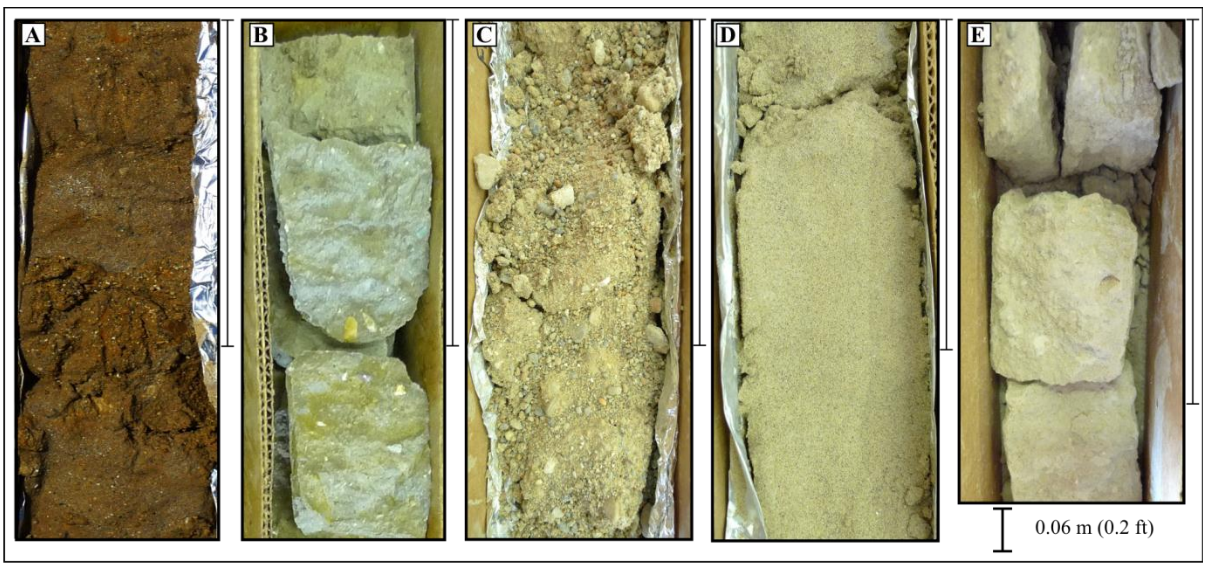

Figure 2.6: Core photographs including: A) paleosol developed into older glacial sand and gravel showing typical oxidation of material and weathered clasts; B) massive silt loam diamicton with small clasts throughout; C) poorly sorted coarse-grained sand and gravel; D) fine to medium massive sand; and E) dense and compact silt and clay (see Appendix A pg. 95 for photographs of all examined continuous cores).

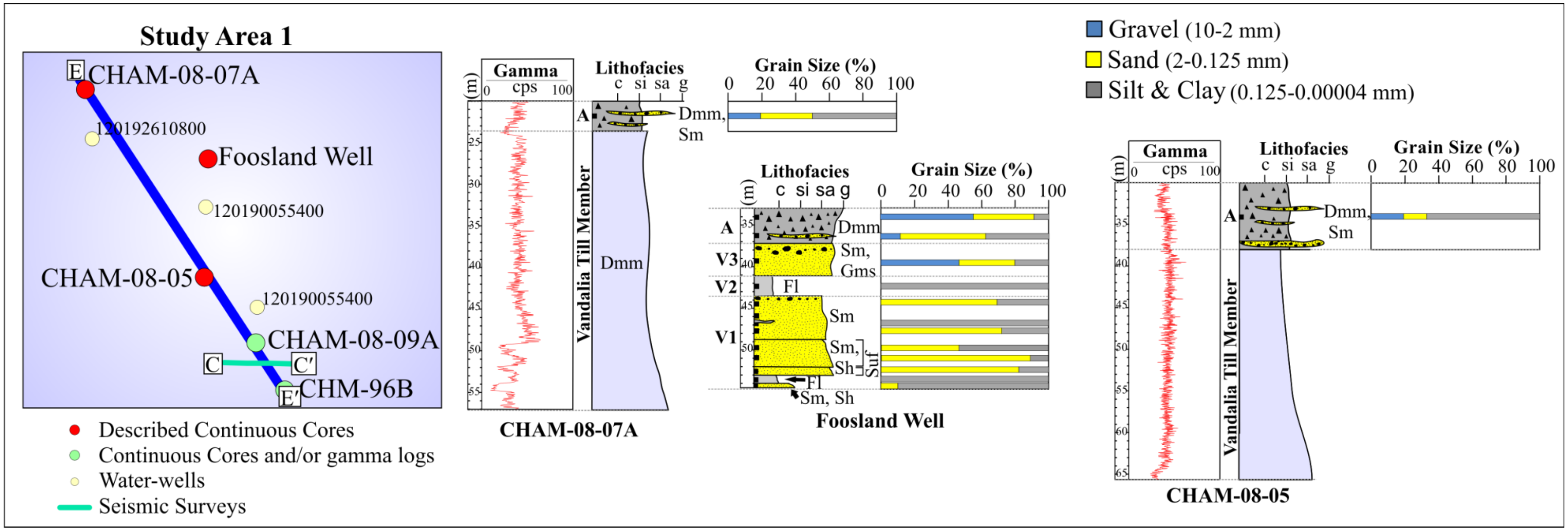

Figure 2.7 A: Defines facies for three examined continuous cores outside and within the Champaign valley margins. Core descriptions for both Figure 2.7A and 2.7 B includes: unit thickness, gamma log, lithology, and modal grain size. Individual facies are shown vertically in the lithofacies section. Distinct facies are outlined as sediments that physically differ from the underlying and overlying sediments. In study 1, unique packages of facies that are closely related to each other have been grouped into facies assemblages V1-V3 that are situated within the valley or A, which in-fills or overlies the valley (see Appendix A pg. 95 for sediment descriptions and photographs, Appendix B pg. 132 for digital files of grain size analyzes, and Appendix D pg. 143 for grain size statistics). (See Table 2.2 for material symbols and lithofacies coding scheme).

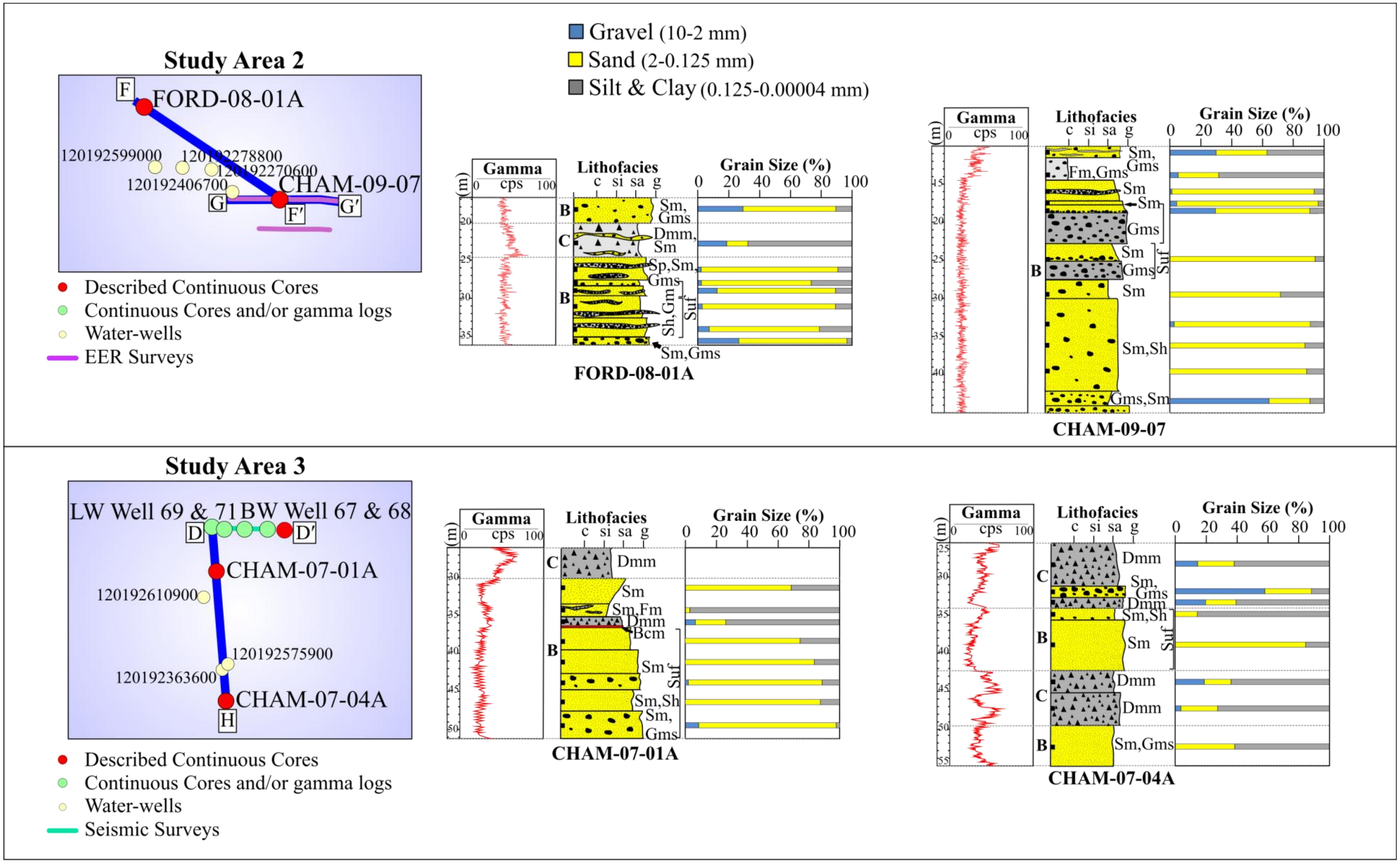

Figure 2.7 B: Studies 2 and 3 show continuous cores, which exhibit vertically repeated facies assemblages B and C of the tabular unit.

2.4.2.2 Sand and Gravel

Coarse-grained sediments in the Glasford deglacial unit range from poorly-sorted sand with pebbles and cobbles (Figure 2.6 C) to massive or bedded fine sand (Figure 2.6 D). Sand dominates the facies, with thin beds of gravel or as gravelly sand containing approximately 5-20% gravel (e.g., facies assemblage B in CHAM-09-07, Figure 2.7 B) with varying amounts of silt and clay (e.g., facies assemblage B in FORD-08-01A, CHAM-09-07, CHAM-07-01A, and CHAM-07-04A, Figure 2.7 B). The sand and gravel of this facies range from yellowish-brown, brown to gray (2.5Y 5/2) in colour (Figure 2.6 C and Figure 2.6 D). This facies includes variable clast content. Similar to the diamicton facies, lithologies include: chert, dolostone, limestone, siltstone, sandstone, and shield lithologies. Rounding of clasts is variable (i.e., sub-angular to sub-rounded) and clast size ranges from small pebbles (5-10 mm) to very large pebbles (10-30 mm). Examination of this facies established the approximate abundance of sand lithologies including: quartz, rock fragments (e.g., sandstone, siltstone, dolostone, and limestone, granite, etc.), and feldspars. The sand and gravel facies have a typically high percentage of quartz ranging from approximately 55-95% of analyzed grains. Rock fragments are less abundant in sand samples (i.e., approximately 5-15%) followed by feldspars (i.e., approximately 2-10%).

Table 2.2. Material symbols and lithofacies coding scheme.

Symbols	Lithofacies Code	Code Description
Diamicton	Dmm	Diamicton: matrix-supported massive.
Gravel	Gm	Gravel: clast-supported, massive.
	Gms	Gravel: matrix-supported, massive.
Sand	Sm	Sand: massive.
	Sh	Sand: very fine to coarse and horizontally/plane bedded or low angle cross-laminated.
	Suf	Sand: upward-fining.
Silt & clay	Fm	Silt & clay: massive.
	Fl	Silt & clay: fine laminations often with minor fine sand and very small ripples.
Boulder	Bcm	Boulder: clast-supported, massive.

Modified from Benn and Evans 1998

The sand and gravel is massive (Sm), horizontally bedded or laminated (Sh). In some cases, a well-developed internal stratification has been obscured or removed by deformation caused by the drilling process; however, some plane and cross-laminated beds have been preserved in some instances. In some cores, the sand fines upwards (Suf) and can be identified in continuous cores based on the logs of natural gamma radiation and grain size data (i.e., indicated by Suf in Figure 2.7 A and Figure 2.7 B). In addition, the sand and gravel facies is generally loose to slightly compacted (Figure 2.6 C and Figure 2.6 D) and has a moderate- to- high porosity depending on grain size and degree of compaction.

2.4.2.3 Silt and Clay

These deposits of fine-sediment include variable amounts of silt and clay, and the overall texture depends on local depositional conditions and grain size of the material supplied. The silt and clay facies include massive or laminated clay or silt with minor amounts (approximately 10-25%) of sand and gravel (i.e., represented by Fm in CHAM-09-07, Figure 2.7 B). In the examined cores, the silt and clay facies has gradational contacts with the sand and gravel facies (e.g., facies assemblage V2 in Foosland, Figure 2.7 A). The silt and clay are predominantly gray in colour (10YR 5/1) (Figure 2.6 E). Fine-grained facies contain few clasts, up to approximately 5% of the bulk sample. When clasts are present they are similar lithology to clasts previously described in other facies types and include minor amounts of shale. Clasts are angular to sub-rounded and sizes range from medium pebbles (6-10 mm) to very large pebbles or cobbles (12-45 mm). In some cases, sedimentary structures such as horizontal laminations (Fl) are preserved.

2.5 Facies Assemblages

Facies and facies associations have been grouped into distinct assemblages that are interpreted to be genetically-related. This grouping is useful to recognize and visualize assemblages of facies that in-fill the Champaign valley (i.e., facies assemblages V1-V3) and those deposited later in the deglaciation that form the tabular body (i.e., remaining deglacial sediments including facies assemblages A-C) (Figure 2.8). Facies correlations were made from descriptions of cores (location provided in Figure 2.3), material descriptions from geologic logs, and borehole geophysical data in the study area. Each facies assemblage identified provides information about a specific group of facies, its position with respect to underlying and overlying units, and sediment characteristics. These assemblages are defined informally within the deglacial sequence and are described below.

2.5.1 Champaign valley

Facies assemblages V1-V3 represent sediments preserved in the Champaign valley. The key continuous core for the valley-fill assemblages is the Foosland Well (Figure 2.7 A). This continuous core does not intercept the Vandalia Member till at a depth of 24-38 m (78-124 ft) where nearby boreholes (i.e., CHAM-08-07A or CHAM-08-05) intercept significant thicknesses of the Vandalia Member till at this depth. This lack of till in the borehole of the Vandalia Member till is assumed to be part of the Champaign valley, the same buried valley system as the one identified along seismic profile C-C′ and D-D′ in Figure 2.5 located 11 km (6 mi) to the south of the Foosland Well.

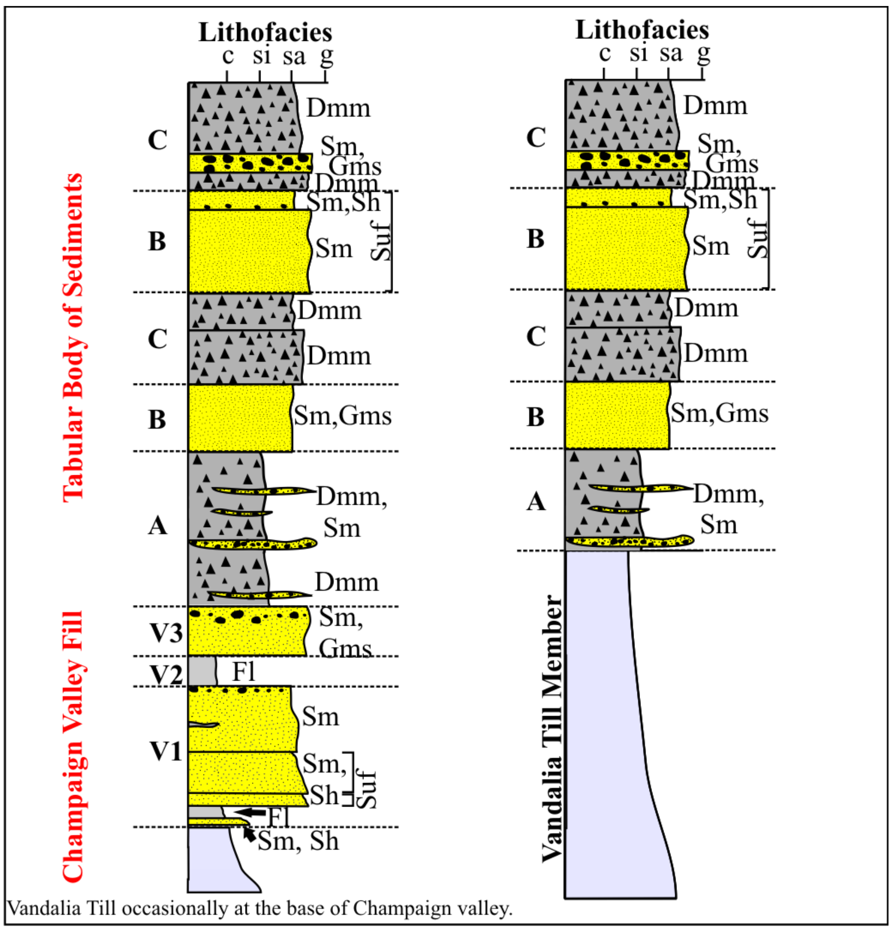

Figure 2.8: Generalized succession of facies assemblages of the Glasford deglacial unit. The Champaign valley includes facies assemblages V1-V3, and facies assemblages A-C of the tabular unit overlies the facies that reside in the valley. These facies assemblages are not found in all boreholes as they are discontinuous across the study area. Facies assemblages not to scale.

The facies assemblages of the Foosland Well are thus interpreted to represent the material in-filling the Champaign valley system and are distinguished from the material forming the tabular unit. Therefore, as shown in Figure 2.8, lithofacies V1-V3 fill the valley and these assemblages are overlain by the remaining tabular deglacial facies assemblages (see section 2.5.2 below) and as a result, the valley-fill sediments represent the oldest deposits assigned to the Glasford deglacial unit.

2.5.1.1 Facies Assemblage V1: Basal sand and gravel

Facies assemblage V1 is a thick succession of very fine to coarse sand, or gravelly sand. More specifically V1 mainly includes: 1) very fine- to coarse-grained sand that is occasionally horizontally bedded; and 2) silt and clay-rich material with fine-laminations overlying the bottom of the Champaign valley (facies assemblage V1 in Foosland Well, Figure 2.7). Sediments overlying the fine-grained material consist of sand characterized by a clear fining-upward succession (denoted by Suf in Foosland Well at 48.8-53.9 m or 160-177 ft, Figure 2.7 A), which is identified in some continuous cores, as well as areas of massive sand. V1 is apparent in cross-section E-E′ (Figure 2.9) in one continuous core (Foosland Well) associated data sources (CHM-96B) and four water-well descriptions (refer to Figure 2.3 for locations). V1 is a discontinuous unit, located primarily at the centre of the Champaign valley. V1 laterally terminates on the undulating topography of the valley floor (refer to valley floor topography, Figure 2.4). In the Foosland Well and other boreholes where V1 has been inferred, the total thickness is approximately 11 m (36 ft).

2.5.1.2 Facies Assemblage V2: Lower silt loam diamicton and fine-grained sediment

Facies assemblage V1 is discontinuously covered with diamictons and fine-grained sediments that form facies assemblage V2 (Foosland Well, Figure 2.7 A). V2 is a complex assemblage of silt loam diamicton and laminated and/or massive silt and clay. Because this unit is relatively thin it is expected to be laterally discontinuous. It is well-defined in one continuous core (i.e., Foosland Well, Figure 2.7 A). V2 materials in the Foosland Well (Figure 2.7 A) include: clay with some silt that exhibit fine laminations. Sediments adjacent to V2 (i.e., cross-section E-E′, Figure 2.9) include silt loam diamictons; however, due to limited high-quality facies data in the Champaign valley, small unit thicknesses, and heterogeneity of materials; no distinction was made between diamicton and fine-grained sediment. Cross-section E-E′ (Figure 2.9) shows V2 at the middle of the Champaign valley and the unit is thought to pinch-out towards the valley walls. The overall thickness of V2 is approximately 3 m (9 ft).

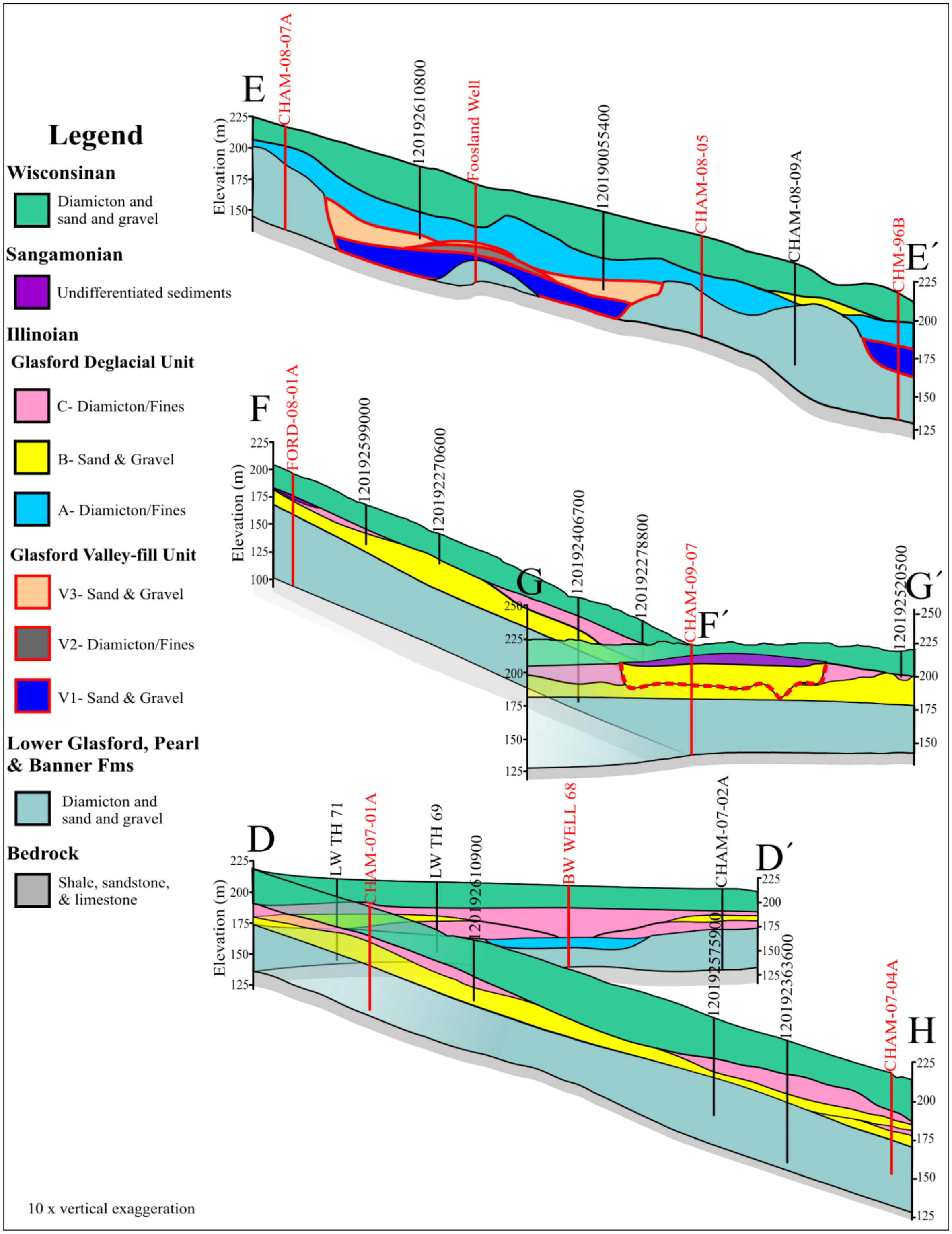

Figure 2.9: Cross-section studies 1-3 created from described continuous cores (highlighted in red) and associate gamma logs, water-wells descriptions, seismic reflection and EER data.

2.5.1.3 Facies Unit V3: Upper sand with gravel

Facies unit V3 is composed mainly of fine to medium sand with higher amounts of gravel near the top of V3 (i.e., at a depth of 36.5-37.2 m or 120-122 ft in Foosland Well, Figure 2.7). Based on descriptions from water-well records throughout the Champaign valley, V3 is interpreted to drape the underlying deposits on the valley sides (as shown in E-E′, Figure 2.9), although it is occasionally more extensive laterally forming a tabular unit overlying V1 and V2 (e.g., E-E′ in the Foosland Well, Figure 2.9). V3 is primarily massive sand (Sm) and no sedimentary structures were observed in examined cores. However, this facies description is based on a single core and further drilling in the valley would be needed to fully document this assemblage. The thickness of V3 is estimated at approximately 4.5 m (15 ft), but is based on limited data for this unit.

2.5.2 Tabular Unit

As shown in Figure 2.4, deposits of the Champaign valley are overlain by an extensive tabular body of sediments that belong to the Glasford deglacial unit. These assemblages are subdivided into three facies assemblages described below.

2.5.2.1 Facies Unit A: Diamicton with sandy interbeds

The deglacial sediments that form the basal part of the tabular unit, and partially infills and covers the Champaign valley as well as the Vandalia Member till throughout the study area consist of a basal, discontinuous highly-compacted diamicton (e.g., CHAM-08-05 and CHAM-08-07A, Figure 2.7A; and E-E′, Figure 2.9). Where this diamicton directly overlies the Vandalia Member till, the contact is marked by a clear break in the gamma log (e.g., CHAM-08-07A, Figure 2.7 A). This contact is correlated with the undulating reflector at approximately 55 m (180 ft) depth along the seismic profiles (Figure 2.5) and, which extends across the top of the Champaign valley separating the valley from the tabular unit. Facies assemblage A also discontinuously caps the top of the Champaign valley and/or drapes the valley sides (Foosland Well, Figure 2.7 A). Generally, discontinuous interbeds of sandy material are abundant near the bottom of the succession (as indicated by 22.3-24.1 m or 73-79 ft in CHAM-08-07A and; 33.8-38.7 m or 111-127 ft in CHAM-08-05, Figure 2.7 A). Therefore, there is an overall fining-upward trend, ranging from a very sandy diamicton to silt loam diamicton. In some cores, this assemblage is found to compose the entire thickness of the Glasford deglacial unit (e.g., CHAM-08-05 and CHAM-08-07A, Figure 2.7 A). This unit has variable thicknesses ranging 4 to 8 m (13-26 ft).

2.5.2.2 Facies Units B: Sand with gravel beds

Facies assemblage B consists of coarse and/or fine-grained sand with beds of gravel and pebbles (e.g., 24.7-36.3 m or 81-119 ft in FORD-08-01A, Figure 2.7 B). Assemblage B is discontinuous across the study area and overlies sediments (V1-V3) in the Champaign valley as well as facies assemblage A (e.g., BW Well 68 in D-D′, Figure 2.9) when present in the glacial sequence. In some areas, assemblage B directly overlies the Vandalia Member till (e.g., G-G′, Figure 2.9). This assemblage appears to form a significant portion of the tabular unit based on several boreholes where this facies is found at a consistent elevation of 175-195 m (574-639 ft) (e.g., D-H and F-F′, Figure 2.9). However, facies assemblage B is significantly thicker in at least one high-quality borehole (CHAM-09-07) extending up the sequence at higher elevations around 200 m (656 ft). One EER profile (G-G′, Figure 2.10) intersects this borehole that has detailed data and clearly reveals the existence of a narrow buried channel. Other EER profiles in the study area (see Figure 2.3 for profile locations) provide evidence for discontinuous buried channels that are in-filled with sand and gravel.

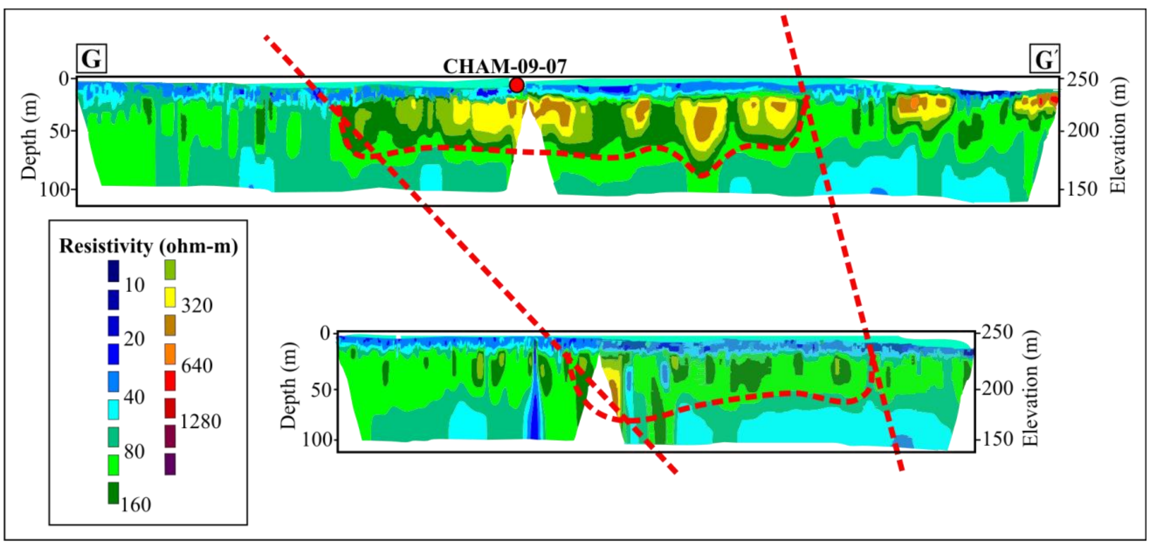

Figure 2.10: Cross-section of buried channel (see Figure 2.3 for EER survey locations). Red dotted line outlines the interpreted extent of the buried channel on the EER profile. Higher resistivity values (indicated by red, brown, yellow, and light green colours on the EER survey) outline areas of sand and gravel of facies assemblage B (Modified from Stumpf and Dey in press).

These buried channels are found at higher elevations than the Champaign valley system (V1-V3) described previously. The sand and gravel material found within the channels is indistinguishable from that of facies assemblage B described in FORD-08-1A and other boreholes intersecting the tabular unit and is thus grouped with facies assemblage B, although the sand and gravel within these channels are younger and could have been deposited in a different depositional environment. This assemblage constitutes a significant portion of the Glasford deglacial unit ranging from approximately 4-21 m (12-69 ft).

2.5.2.3 Facies Unit C: Silt loam diamicton and/or fine-grained material

Facies assemblage C includes diamicton with minor beds of sand and gravel and/or silt and clay (e.g., 20.4-24.7 m or 67-81 ft in FORD-08-01A, Figure 2.7 B). Similar to assemblage B, the diamicton and/or fine sediments of assemblage C are discontinuous across the study area and in some areas, overlie the Vandalia Member till (e.g., D-D′, Figure 2.10). Assemblages B and C are separated by a gradational contact. In some areas, these assemblages are repeated as another cycle of sediments above (e.g., D-D′ and D-H, Figure 2.9). These assemblages represent the upper deposits of the Glasford deglacial unit. Total thicknesses of assemblage C ranges from 4-9 m (13-30 ft) (see Appendix A pg. 95, Figure A.4 and Figure A.7 for photographs of repeated facies assemblages C and B in continuous cores).

2.5.3 Outcrop Exposures

The Higginsville section is a large outcrop exposed on the Middle Fork River in Vermillion County, Illinois (Figure 2.11) (location provided in Figure 2.3). A thick cover of glacial sediments from the Wisconsinan overlies the older paleo-surfaces with significant topography, and as a result outcrops are sparse; however, along modern rivers glacial deposits have been exposed. The Higginsville section is located east of the study area (Figure 2.3), but the stratigraphy exposed provides detailed information about the tabular unit of the Glasford deglacial unit and is an analogue for the buried deglacial materials investigated nearby, and the previously described facies (section 2.4.2) are present at this site. The diamictons at the Higginsville section are predominantly silt loam (Dmm) containing approximately 5-20% clasts. Clast lithologies include: chert, dolostone, limestone, and sandstone and clast sizes range from granule to large. Beds of sand and gravel were also noted and the sand and gravel facies at the Higginsville section also exist as discrete units and are predominantly matrix-supported sand (Sm) with approximately 5% gravel. The sand is moderately- to- well sorted with sub-angular to sub-rounded grains. In some cases, horizontal laminations (Sh) are preserved in the sand (Figure 2.11). Towards the northern part of the section the upper portion of the sand and gravel facies show deformation structures (i.e., folds truncated and overturned to the south) (Figure 2.11), which are indicative of glaciotectonites processes. Small amounts of fine-grained material were also identified at the Higginsville section for this study. In most cases these units were noted as small layers within sand and gravel units (see Appendix A pg. 95, Table A.8 for detailed description of the Higginsville section, and Figure A.8 and Figure A.9 for outcrop photographs).

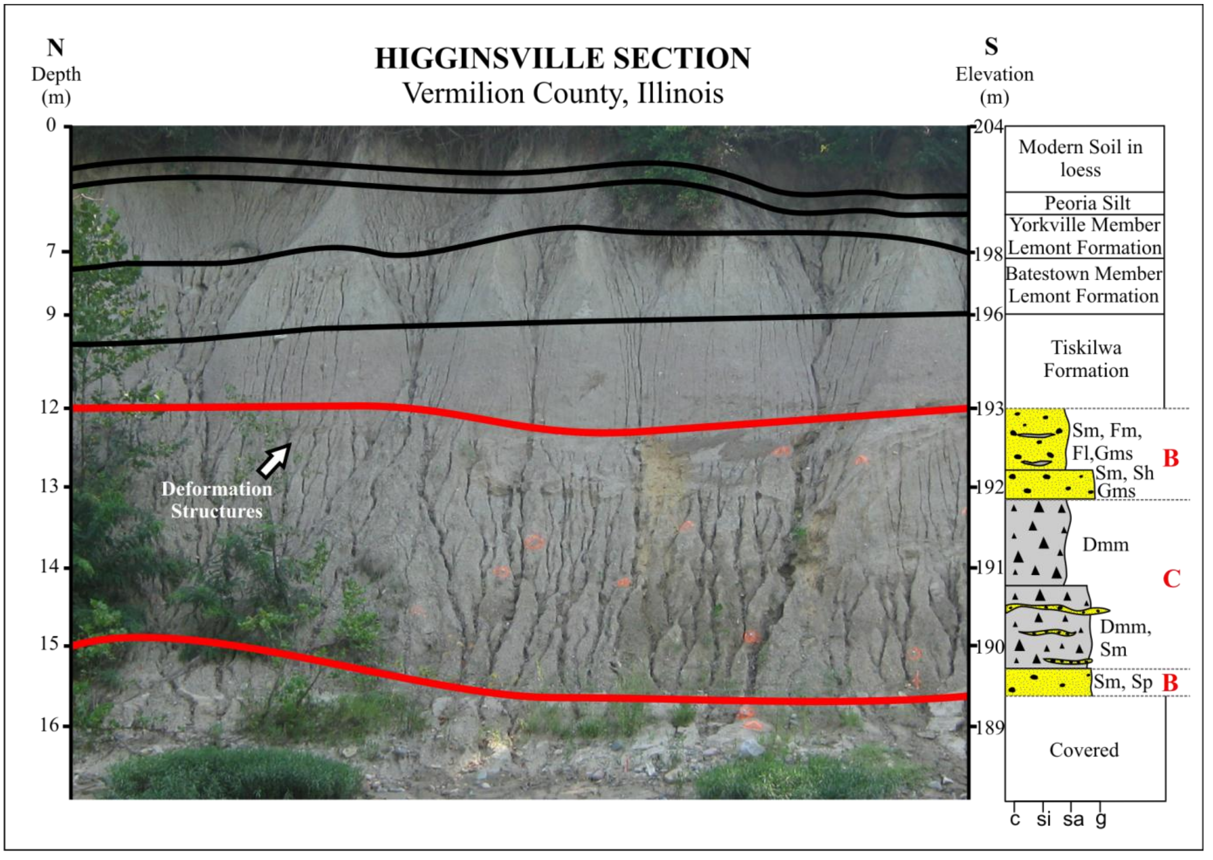

Figure 2.11: Higginsville section located 7.90 km (4.91 mi) outside the study area. This section provides sediment exposure of the Glasford deglacial unit, which was previously defined as the Radnor Member till. In its type section (Jubilee College Section in Radnor Township, Illinois) the Radnor Member till is described as silty to clayey diamicton, but the deposits found at the Higginsville Section include: packages of sand and gravel and silt loam diamicton (Johnson et al. 1972). Deformation structures are also noted at the section, but not visible at the scale of this photo.

2.6 Reconstructions

Current geological understanding of the Glasford deglacial unit is limited; however, the heterogeneous complexes that in-fill the Champaign valley and the overlying tabular unit described in the facies descriptions (section 2.4.2) and facies assemblages (V1-V3 and A-C, sections 2.5.1 and 2.5.2) are interpreted as ice-contact and/or ice-marginal sediments that were deposited during the Illinoian deglaciation. The following provides interpretations of the sediments preserved in the Champaign valley and tabular unit as well as the origins of the features.

2.6.1 Formation of the Champaign Valley

The Champaign valley that underlies a large portion of the study area (Figure 2.4) is thought to be associated with deposition of the Glasford deglacial unit, and discerned by geological information from cores and geophysical profiles. The age of the valley is well constrained to the latter part of the Illinoian stage (MIS 6) because the valley is incised into till of the Vandalia Member and older Illinoian and Pre-Illinoian sediment and the valley fill is overlain by deglacial deposits containing a paleosol (Sangamon Geosol) developed in the upper part.

Similar valleys to the Champaign valley have been encountered in glaciated North America and thought to have formed by varying processes such that comparisons can be made. Table 2.3 lists the key features and characteristics of the Champaign valley in this study as well as selected glacial valley systems from southern Canada, the northeastern United States, and Denmark. Information about the valley systems are used to compare and contrast different morphologies, in-fill processes, and interpreted formation. For this study, two possible origins are proposed for the Champaign valley that developed during the Illinoian deglaciation, which include: 1) erosion by subaerial glaciofluvial processes in a proglacial environment with the advance or retreat of the ice sheet (Figure 2.12); or 2) a subglacial tunnel valley system (Figure 2.12). Subaerial glaciofluvial processes taking place at or beyond the ice-margin may have caused significant erosion of the substratum resulting in a relatively large valley system. Subglacial processes may have also been responsible for the formation of the valley system. Subglacial meltwater, under glaciohydrostatic pressure and flowing on a soft and erosional bed, may cause the erosion and evacuation of sediments forming Nye channels or tunnel valleys (Cofaigh, 1996).

Table 2.3. Buried valley successions in other areas.

Region	Morphology	In-fill	Type
East-central Illinois This study	▪ High width to depth ratio. ▪ Max depth approx. 100 m and width approx. 7.4 km. ▪ Total valley extent unknown.	• Basal sand and gravel, pitted with diamictons and fines, sand and gravel draping valley sides.	Subaerial glacio-fluvial or subglacial tunnel valley.
Medora-Waskada Buried Valley Southwestern Manitoba Hinton et al. 2007	• 1-2 km wide and up to 110 m deep. • Eroded into the bedrock.	• Highly variable throughout the valley. Valley-fill includes: 'till' and mostly fine-grained stratified sediments. • Packages of discontinuous gravel are located at the bottom and middle of the valley.	Subaerial glaciofluvial to subglacial settings.
Prairie region of Canada and parts of northern USA Sharpe 2009	• Low width to depth ratio. • Several tens of meters in average depth.	• Sand and gravel at the base of the valley. • Mostly diamicton with some sand beds in-filling remaining portions of the valley.	Buried glaciofluvial valleys.
Buried Quaternary valleys in western Denmark Sandersen and Jørgensen 2003	• Depth of the buried valleys range from 25 to 350 m (some actual depths remain uncertain). • Approximately 1-2 km wide over an estimated distance of 25-30 km.	• Sand and gravel (mostly melt water deposits) and a large amount of diamicton. • Sediments types vary both laterally and vertically with no distinct pattern.	Buried tunnel valleys.

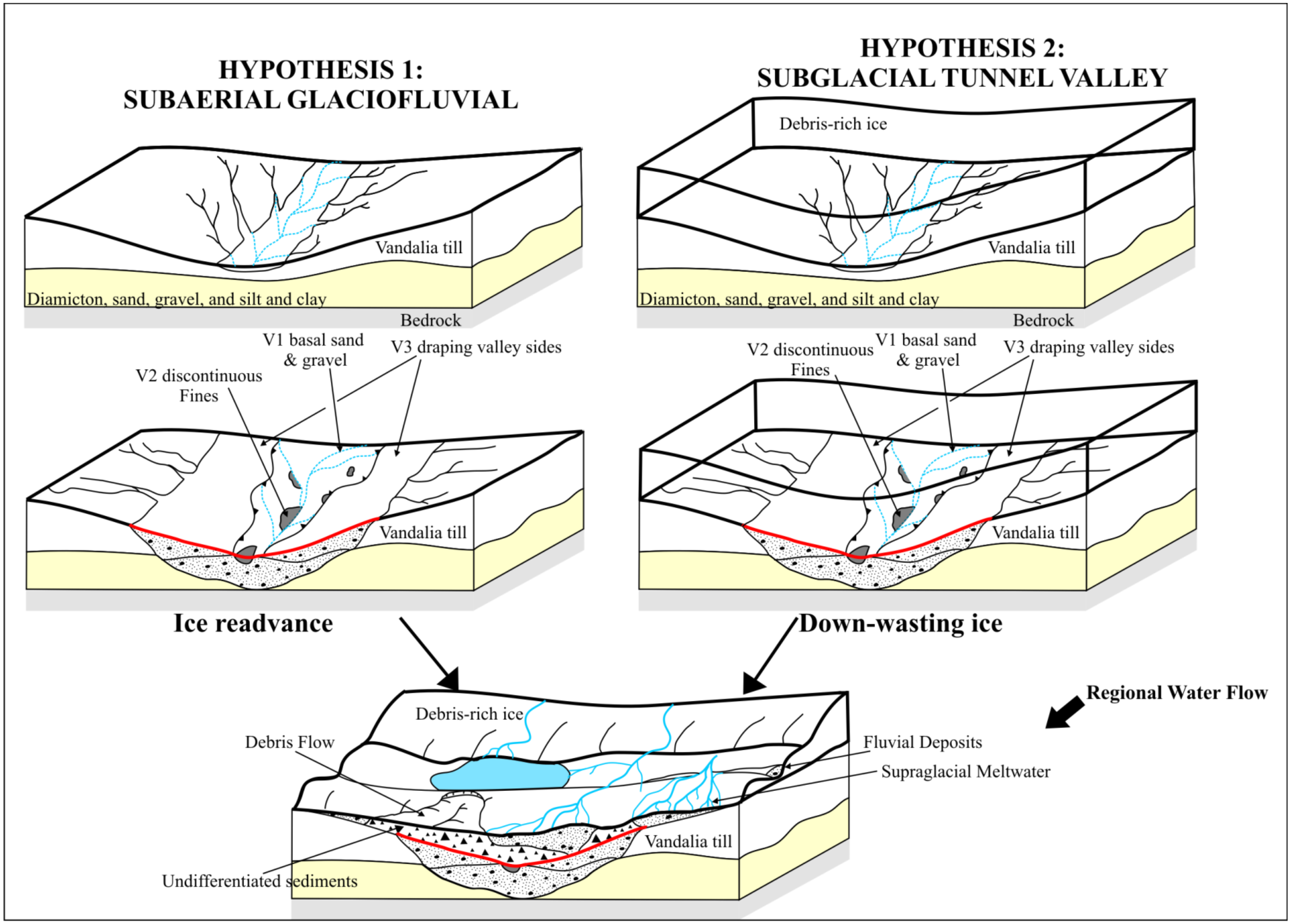

Figure 2.12: Two conceptual models for the depositional history of the Glasford deglacial unit. Hypothesis 1: subaerial erosion of Vandalia Member till and subsequent in-fill of valley. Hypothesis 2: initial incision of Vandalia Member till under glacial ice and in-fill of valley. Burial of valley under ice-marginal conditions result in tabular facies assemblages. Advance or retreat of glacial ice is unknown.

Different mechanisms have been proposed for tunnel valley formation and they broadly fall into two categories: steady-state and relatively slow mode (e.g., Cofaigh 1996) or a catastrophic and very rapid mode (e.g., Russell et al. 2003; Hooke and Jennings 2006). Regardless of the exact mode of formation, these valleys are distinct from subaerial glaciofluvial valleys as they are characterized by undulating longitudinal profiles with isolated areas of overdeepening. In the subglacial environment ice as well as meltwater under glaciohydrostatic pressure can erode deeply in the substrate. A closer look at the topography on the Champaign valley floor (Figure 2.4) suggests that the valley is indeed characterized by an undulating valley profile. However, the valley floor topography shown in Figure 2.4 should be regarded as preliminary, constructed primarily from geologic logs recorded during drilling of water-wells and seismic data from limited geophysical surveys. Thus, uncertainty remains on the exact dimensions of the valley and topography of the valley floor because of limited data and variability in the accuracy of information. However, current reconstructions of the valley dimensions show a significant size difference (i.e., width) when compared to the other example valleys outlined in Table 2.3 and the size difference could be the result of a series of interconnected valleys that at the scale of this study cannot be differentiated, and further work would be needed to make this distinction.

2.6.1.1 Valley-fill

Sedimentation in the Champaign valley may be due to several processes and the events that deposited the valley-fill may not be related to the ones that formed the valley. In general, the Champaign valley is filled by interstratified, massive, and bedded sand (V1 and V3), as well as by laminated to massive silt and clay, and diamicton (V2). The variable sand facies developed during different meltwater flow intensities occasionally producing horizontal laminations (indicated by Sh in Figure 2.7 A) or rapid sedimentation in water flow producing massive sands (e.g., Sm, Figure 2.7 A). Waning flows in a glaciofluvial to glaciolacustrine environment created the laminated and/or massive silt and/or clay (e.g., Fl, Figure 2.7 A). Possibly debris-flow mechanisms may have deposited the diamicton facies; however, the diamictons are difficult to determine their exact depositional environment when using primarily borehole data. Large-scale features, often seen in field outcrops and useful for interpreting depositional environments cannot be inferred from the cores. Consequently, the diamicton (e.g., facies assemblage A) may have formed from two possible processes: 1) debris-flow processes, which could have capped the top of the valley with diamicton (Figure 2.12); or 2) subglacial processes, which could be linked to valley formation (Figure 2.12). Overall, valley-fill successions are linked to ice-contact or ice-marginal glaciofluvial processes of varying energy and possible debris-flow or subglacial processes active during deglaciation.

2.6.2 Origin of Tabular Units

The tabular body that overlies the valley-fill and extends beyond the Champaign valley margins consists of a highly heterogeneous package of interstratified sand and diamicton, and discontinuous layers of fine-grained material. The coarse-grained sorted material is interpreted to be glaciofluvial in origin, and as previously discussed; the diamicton is interpreted to be created from debris-flow processes or in the subglacial environment below the ice sheet (Figure 2.12). A readvance of ice would be required to deposit the Radnor Member till, and thus the top horizons of underlying units would have erosional contacts or characteristics of subglacial deformation. Deformation structures were noted at the Higginsville section however, these structures are mostly likely due to the advance of ice during the Wisconsinan, which was responsible for depositing the Tiskilwa Member till. No detailed study of these deformation structures was undertaken, yet visual analysis shows the structures to be more abundant near the top of the unit (i.e., the Glasford deglacial unit). This minimal depth of deformation and the small total cumulative strains suggested at the Higginsville section may be indicative of some glaciotectonites (e.g., Benn and Evans 1996; Philips et al. 2002). As a result, pre-deformational sedimentary assemblages are still recognizable and not characteristic of a subglacially deposited till. Therefore, these deformation structures are not linked to ice advance depositing the Radnor Member till. Furthermore, multiple cycles of the B and C assemblages are noted vertically in cores, rather than upward thickening of diamicton units associated with typical ice advance sequences. Therefore, as a part of this study the complex successions of highly heterogeneous meltwater deposits and diamicton preserved in the subsurface record suggest a dynamic ice-marginal system with fluctuating meltwater energy levels that are typical of this environment. Although the most likely origin for the highly heterogeneous sediment assemblages is through ice-marginal processes, these processes could be associated with ice readvance or retreat; however this has yet to be established.

2.7 Wider Implications

Consistent with the ice-contact and/or ice-marginal interpretation, the Glasford deglacial unit may have a similar formation to ice-contact landforms of southwestern Illinois. The ice-contact landforms, named the Ridged-Drift, were also deposited during the Illinoian stage (MI6) (Grimley and Philips 2011). These ice-contact landforms comprise the Hagarstown Member, which consists of interstratified facies including: mixed or alternating layers of coarse sand and gravel, fine sand, diamictons, silt, and/or silty clay (Grimley and Philips 2011). Similar to the Glasford deglacial unit, the Hagarstown Member lies stratigraphically above the Vandalia Member till and contains the Sangamon Geosol at the top (Grimley and Philips 2011; Jacobs and Lineback 1969). Contrary to the Glasford deglacial unit of east-central Illinois, the Ridged-Drift of the Hagarstown Member represents constructional features, rather than erosive features interpreted for the Champaign valley in the Glasford deglacial unit. However, as east-central Illinois is covered by thick Wisconsinan deposits that do not cover southwestern Illinois, constructional hills are not visible on the otherwise flat Illinoian Till plain.

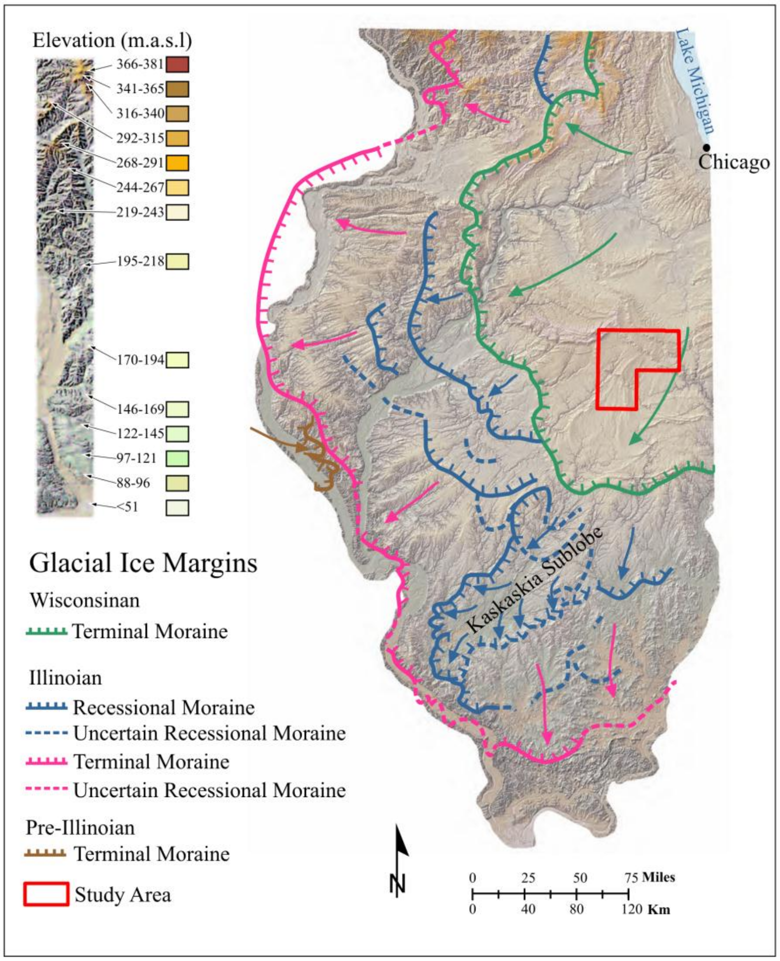

Figure 2.13: Ridged-drift of southwestern Illinois formed along recessional moraines of the Kaskaskia Sublobe during the Illinoian. Southwestern Illinois is not covered by deposits of the Wisconsinan glaciation and therefore the ridged-drift is exposed at the land surface. However further north in the study area, Wisconsinan deposits completely cover the Illinoian deposits and recessional moraines formed during the Illinoian glaciation are not visible at land surface. Although, processes described by Grimley and Philips (2011) could be responsible for the formation of the Glasford deglacial unit. This figure is modified from an illustration by Grimley and Philips (2011).

Current hypotheses for the Ridged-drift include a glacial sublobe (i.e., the Kaskaskia Sublobe). The hypothesized sublobe was thought to be dynamic during the Illinoian deglaciation (i.e., late MI6) as an active area of debris-rich ice moved into topographically restricted parts of southwestern Illinois (i.e., the Kaskaskia Basin) resulting in ridges (e.g., moraines, eskers, and kames) at ice-marginal positions as the sublobe progressively retreated. Thus, highly complex assemblages of ice-marginal sediments are maintained in the ridges, and to a lesser extent, surrounding the landforms. Sediments of the Hagarstown Member and the Glasford deglacial unit are both heterogeneous and complex deposits, and as a result, it may be possible that the same sublobe mechanism maybe responsible for the Glasford deglacial unit and the associated Champaign valley.

2.8 Conclusions

Continuous cores and near-surface seismic methods were used to improve the description and understanding of the Illinoian deglacial record in east-central Illinois. Facies in the Glasford deglacial unit include: 1) massive, matrix-supported diamicton; 2) interstratified sand and gravel; and 3) fine-grained massive or laminated sediment. Subsequent, grouping of genetically-related facies into facies assemblages (i.e., units A-C and V1-V3) was critical in developing an understanding of the subsurface geometry and lateral extent of the deglacial deposits. An updated geological framework also aided in the identification of the large Champaign valley associated with the Illinoian deglaciation on the basis of stratigraphic relationships with paleosols and other marker beds. The identified valley emplaced into a regional till (i.e., Vandalia Member till) and valley-fill consisting of Glasford deglacial sediments includes: significant deposits of sand and gravel, coarse-grained sediments draping the valley sides, discontinuous diamicton units, and fine-grained sediment layers. The origin of the valley and its in-fill history appear to be complex and uncertainty remains on the relation of events. Preliminary interpretations suggest that subaerial glaciofluvial processes or a subglacial tunnel valley with progressive valley in-fill are the most likely origins. Overall, further drilling and geophysical surveys should be directed towards better characterizing the Glasford deglacial unit and the geological complexities that exist in the Champaign valley and overlying deposits as they are a vital source of local water resources. Improved delineation of the extent of the Champaign valley and additional characterization of the tabular deglacial facies will aid in the more complete understanding of the Glasford deglacial unit and advance applied geology studies in Illinois.

Chapter 3

Three-dimensional geological modeling of subsurface hydrofacies assemblages forming a heterogeneous aquitard/aquifer 'hybrid' unit

Overview

Three-dimensional geological modeling of highly heterogeneous deposits assigned to the Late Illinoian (Marine Isotope Stage 6) deglaciation was undertaken as part of a regional groundwater study in east-central Illinois. These deposits, informally referred to as the Glasford deglacial unit, overlie a regional aquitard and a deeper aquifer of regional importance. This unit contains relatively shallow discontinuous aquifers that are utilized for domestic water supplies. These supplies can be affected by increased water usage, climate change, and extraction of groundwater from deeper, higher capacity wells. An important challenge in this study was to model these aquifer and aquitard geometries and their internal heterogeneity. In this part of Illinois, deposits of the Illinoian glaciation, including the Glasford deglacial unit, are buried in the subsurface and are not widely exposed at the land surface. Furthermore, many sediment layers are discontinuous, complicating the task of modeling aquifer connectivity. Using available data, which includes descriptions of continuous cores, geophysical data, and geologic data from driller's logs, a 3-D geological model was constructed using gOcad® (Paradigm™), a 3-D geomodelling software. The model consists of discrete surfaces with an irregular triangulated mesh representing the top of the Glasford deglacial unit as well as key internal layers, which forms the framework of a 3-D cellular partition that allows for mapping internal properties of hydrostratigraphic units. Major heterogeneities have been recognized and mapped at regional scale represented by the fine- and coarse- sediment facies that comprise 46% and 54% respectively of the unit volume. The Glasford deglacial unit is a complex subsurface ice-marginal package of sediments, which challenges the aquifer-aquitard concept. These types of units are better described as hybrid layers (part-aquifer/part-aquitard). The occurrence of complex hybrid layers and associated underlying erosional surfaces formed during the Illinoian deglaciation can impact the integrity of regional aquitard units that overlie deeper aquifers. It is important to examine these units in modeling studies, not just the regional aquifers. Yet, this study highlights the difficulty in representing the complexity of hybrid assemblages at a regional scale. However, attempts to model heterogeneities within a hydrostratigraphic unit are important as similar complex assemblages are prevalent throughout the glaciated regions of North America.

Keywords: 3-D geological models, gOcad, hydrostratigraphy, hydrofacies, east-central Illinois

3.1 Introduction

The population of 15 counties in east-central Illinois is expected to increase from 1.03 million in 2000 to 1.34 million in 2050 (RWSPC 2009). This represents a 30 percent increase in population for the area, leading to increased pumping of available water supplies. In response to increased development and the stresses imposed on water-delivery systems, the Regional Water Supply Planning Committee (RWSPC) for east-central Illinois has outlined the need to develop options for the responsible use of groundwater resources in the area. Consequently, an understanding of the regional hydrogeologic conditions is necessary to make informed decisions as to the sustainable use of groundwater. In this study these hydrogeologic conditions are based on an understanding of the spatial distribution and extent of geologic units (i.e., the geological framework) that controls groundwater flow.

Illinois has one of the most complete terrestrial records of the Quaternary Period. Related sediments average 30 m (100 ft) in thickness and 76-152 m (250-500 ft) thick in bedrock valleys (Piskin and Bergstrom 1975). The sediment record provides evidence for glacial lobe advance and retreat cycles as well as an extensive record of interglacials for at least three glacial-interglacial cycles in the state (see Chapter 2, Figure 2.1) (Hansel and McKay 2010). There is a wealth of stratigraphic knowledge and mapping legacy in Illinois, which has characterized these extensive sediment records. However, further examination of the geological framework of an area is useful to understand the subsurface stratigraphic architecture of Quaternary units at a level of detail appropriate for specific groundwater studies. Mapping and modeling of these complex land-systems are important to address important societal issues such as long-term water supplies. Consequently subsurface information, especially updatable 3-D geological models and derivative map products, show the distribution of unconsolidated deposits and this information is needed by planners and scientists to manage available water resources.

As a part of a groundwater study of the Mahomet aquifer in east-central Illinois completed by Stumpf and Dey (in press), a regional scale 3-D geological model and associated groundwater flow model were created from the land surface to bedrock to represent glacial sediments within and overlying the large Mahomet Bedrock Valley (MBV) (see Chapter 1, Figure 1.5). This regional scale geological model of glacial sediments represents the most significant hydrostratigraphic units in east-central Illinois, and provides a framework suitable for inclusion of subsurface information into a regional scale groundwater flow model being developed by the Illinois State Water Survey (ISWS). A limitation of this model is that it only provides information about the geometry of the major mappable hydrostratigraphic contacts (bounding surfaces) separating laterally extensive aquifers and aquitards. It became clear during the course of the project that some units were highly heterogeneous and that this should be further explored and examined. As a result, geological modeling of deposits assigned to the Glasford deglacial unit that overlie the MBV was undertaken and included development of a ‘Glasford’ geological model. Partitioning of the deglacial unit into potentially mappable depositional features such as regional architectural elements (e.g., the Champaign valley and overlying tabular unit, see Chapter 2) as well as internally consistent hydrofacies assemblages, facilitated in incorporating a higher degree of heterogeneity within the Glasford model and thus refining and updating the original Illinois State Geological Survey (ISGS) geological model for east-central Illinois.

Accordingly, this paper presents the methodology and results of the 3-D geological model of the Glasford deglacial unit in the study area (Figure 3.1), which incorporates information on the internal structure, and hydrofacies assemblages of the Glasford deglacial unit involving 3-D geological modeling of complex ice-contact and ice-marginal sediments. This case study also led us to revisit aspects of the classical hydrostratigraphic concept including unit subdivision into aquifers or aquitards. Consequently, this study will provide a better depiction of subsurface heterogeneous deglacial deposits, which will help assess potential hydraulic connections within the Glasford deglacial unit, water availability in the deglacial unit, and estimate possible connections with surrounding hydrostratigraphic units. All of this will provide improved understanding of the influence the Glasford deglacial unit has on subsurface hydrogeologic conditions above the MBV in east-central Illinois. It may also provide insights and a reference for comparison with other glaciated regions in North America or elsewhere having a similar subsurface geology.

3.2 Study Area

As a part of a regional scale water resources project in east-central Illinois, a 30-township study area was studied to develop the ISGS 3-D geological model and ISWS groundwater flow model. As shown in Figure 3.1, the ISGS 3-D geological model from land surface to bedrock have been produced to incorporate the mappable hydrostratigraphic units (shown in cross-section I-I′, Figure 3.1) in east-central Illinois (Stumpf and Dey in press). In Illinois during each glacial stage (i.e., Wisconsinan, Illinoian, and Pre-Illinoian), different sediments including diamicton, glaciofluvial sediment (primarily sand and gravel) and/or glaciolacustrine sediment (sand, silt, and clay) were deposited and are preserved to various degrees. Assignment of the sediments from land surface to bedrock into hydrostratigraphic units is based on physical sediment properties including colour, grain size, lithology, mineralogy, bedding, and general stratigraphic position (Hansel and McKay 2010).

In this study, the geological modeling focuses on the major internal structures and hydrofacies assemblages of the Glasford deglacial unit within the bounding surfaces contained in the ISGS geological model (Figure 3.2). The sediments in this unit include sand, sand and gravel, diamicton, and silt and clay and have been classified into different hydrofacies assemblages (see Chapter 2). These sediments were deposited in various environments due to a number of different processes (e.g., fluvial/ debris-flow processes, etc.). The deglacial unit is bounded at the bottom by the Vandalia Member till and at the top by deposits correlated to the Wisconsinan. In addition, the Sangamon Geosol developed in the upper part of the deglacial unit and is another stratigraphic marker for the top of the unit. In some areas a large valley, informally named the Champaign valley, incises into the underlying Illinoian and Pre-Illinoian sediments (see the Champaign valley in Chapter 2; or Figure 3.1).

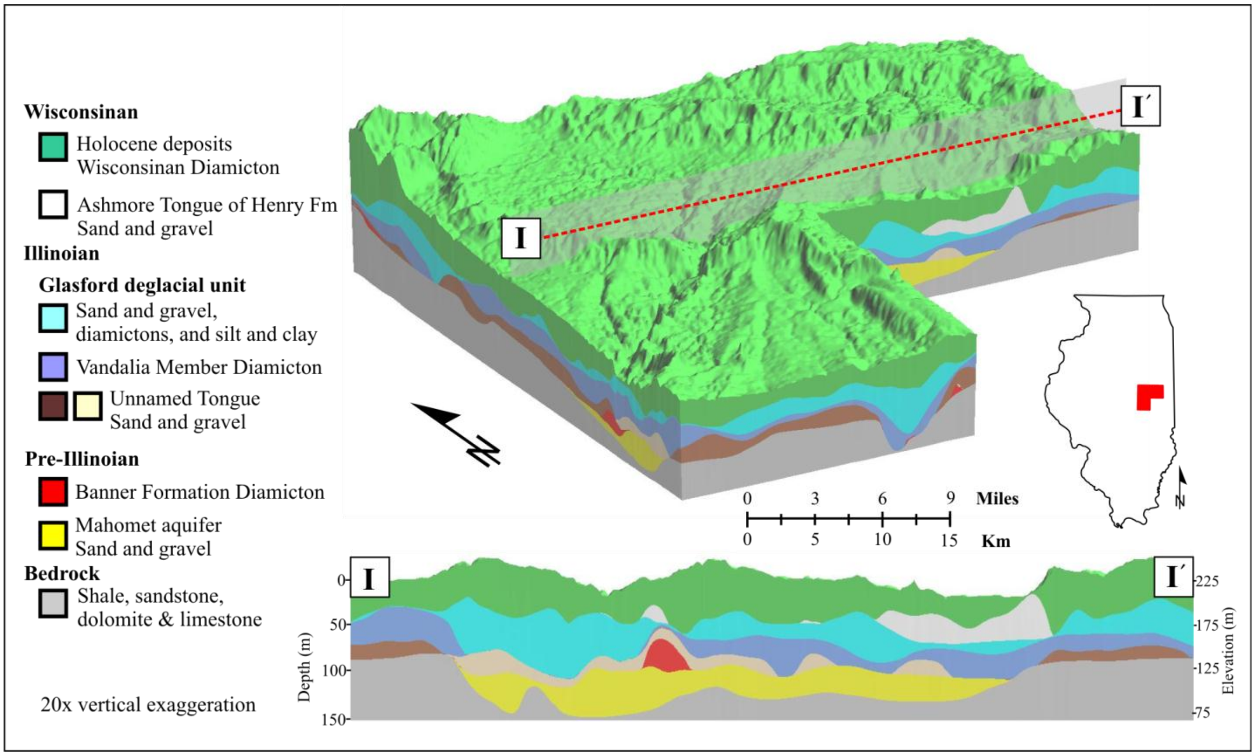

Figure 3.1: 3-D geological model created for a groundwater study in east-central Illinois (i.e., the ISGS model) developed by Stumpf and Dey (in press). The model encompasses 2642 km^2 (1642 mi^2) covering 30 townships (area shaded in red on the inset map of Illinois). Cross-section I-I′ provides an overview of the hydrostratigraphic units mapped from land surface to bedrock including the Glasford deglacial unit and the associated Champaign valley. The Champaign valley is visible on cross-section I-I′ incised into the underlying Illinoian and Pre-Illinoian sediments.

3.2.1 Hydrostratigraphy and Geological Modeling Scale

Hydrostratigraphy is concerned with the identification of subsurface units on the basis of their hydrogeologic properties (e.g., Maxey 1964; Seaber 1988). Conventionally, extensive permeable material is grouped to form aquifer units, whereas extensive material that restricts the flow of water in the subsurface is mapped as an aquitard. The characterization of aquifers and aquitards will vary depending on the scale of the study (Figure 3.2). The large mappable aquifer/aquitard units can be further partitioned into hydrostratigraphic bodies (Figure 3.2), which can be, for example, depositional elements (e.g., buried valley fill, delta, etc.) within an aquifer that can be distinguished from other adjacent aquifer materials on the basis of bulk sedimentologically-derived hydraulic properties (e.g., high to low permeability) (Heinz and Aigner 2003). The scale of the hydrostratigraphic model and the techniques used to characterize the subsurface thus determines the degree of heterogeneity that would be incorporated (Heinz and Aigner

2003). Model scales are variable and depend on the model objectives (e.g., regional 10-100 km or local 1-10 km water supplies), and as a result, some models represent major hydrostratigraphic units as homogeneous with limited internal variability (e.g., aquifer scale) (e.g., Ross et al. 2005) whereas other, more local, models are developed to represent heterogeneities and highly variable sediment (e.g., hydrofacies scale) (Figure 3.2) (e.g., Weissmann and Fogg 1999).

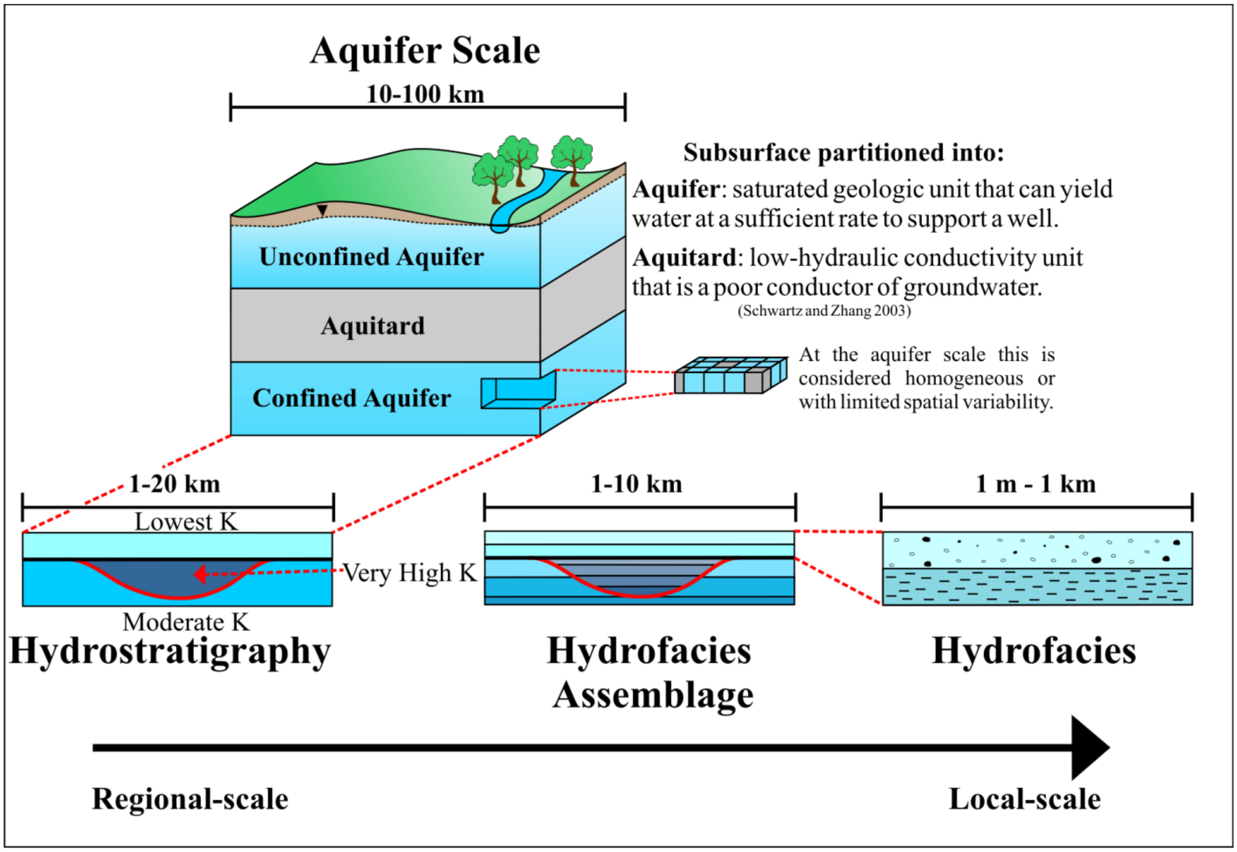

Figure 3.2: The concept of hydrostratigraphy and related subsurface partitioning at various scales from regional to local. Traditional conceptual hydrostratigraphic models subdivide the subsurface into aquifer and aquitard units.

The Glasford deglacial unit is not considered an aquifer or aquitard in a strict sense because of its discontinuous nature and highly heterogeneous character (see Chapter 2). However, the Glasford deglacial unit is important in east-central Illinois and can be relatively continuous, and thus mappable at the hydrofacies assemblage scale (1-10 km, Figure 3.2). There is a need to characterize the heterogeneities in the unit that may affect water flow in the subsurface and possibly into regionally significant aquifers. Thus, the scale of the Glasford model includes the regional bounding hydrostratigraphic surfaces presented in the ISGS geological model (1-20 km) and as a part of this chapter, mappable (i.e., laterally extensive) architectural elements (i.e., the Champaign valley and tabular unit, see Chapter 2; and Figure 3.2) and hydrofacies assemblages (i.e., facies assemblages V1-V3 and A-C, see Chapter 2; Figure 3.2) are incorporated into the Glasford model to examine the relationship between heterogeneous ice-contact and/or ice-marginal sediments and their hydrogeologic properties in the subsurface.

3.3 Methodology

Typically, the early phase of a subsurface geological investigation involves compilation of existing data, development of a project database, as well as data standardization and quality assessment (e.g., Kostic et al. 2005; Ross et al. 2005; Lelliott et al. 2006; Allen et al. 2008; Artimo et al. 2008). For the purpose of the Glasford model, a separate database containing geologic and geophysical information from boreholes and near-surface geophysical data was compiled. The data were then standardized to incorporate the wide variety of data sources in different formats for inclusion in the Glasford model. An important component of this analysis was the ability of visualization in 3-D. The process of computer-based visualization of data at different scales and formats (e.g., maps, sections, boreholes, and geophysical data), which are all integrated in the same spatial framework using geomodelling software, provided a number of advantages over 2-D Geographic Information Systems (GIS) and significantly contributed to the development of the updated geological framework.

3.3.1 Data Compilation, Quality Ranking, and Standardization

Archived subsurface data were fundamental in the development of the geological model due to limited sediment exposures in the study area. A Glasford model database was created from available data for the construction of the geological model including: descriptions of continuous cores, and geologic information contained in driller's log of boreholes for water-wells, engineering tests, and coal, oil and gas exploration. A total of 38 continuously-cored boreholes and geophysical logs, 70 borehole geophysical logs, and 799 logs from boreholes drilled for water-wells were used out of the available 1662 data points in the study area. Each set of data was then standardized to facilitate comparison between detailed descriptions of cores and less detailed information (e.g., geologic logs from water-wells). In this study, the standardization of data from geologic logs of water-wells presented a challenge. This was a result of the highly-variable grammatical structure and material descriptions provided by water-well drillers. Standardization of the unique descriptions in the logs from water-wells was completed to reduce the number of possible descriptions. The standardization scheme used for these logs is shown in Table 3.1. Thirty descriptive lithologies were used to group geologic materials and further simplify the geologic material into twenty coded attributes (Table 3.1) of similar character into single descriptive units for the creation of the Glasford model. The data were also ranked according to general quality criteria (Table 3.2).

Table 3.1. Standardized material coding scheme (After Ross et al. 2005).

Material		Code
Organic		O
Fill		X
Till/ Diamicton		D
Clay		F1
Silty Clay		F1
Sandy Clay		F1-S1
Gravelly Clay		D
Clay and Boulders		D1
Silt		F1
Clayey Silt		F1
Sandy Silt		F2
Gravelly Silt		D
Silt and Boulders		D1
Sand		S
Fine Sand		S1
Medium Sand		S2
Coarse Sand		S3
Clayey Sand		S1-F1
Silty Sand		S1-F1
Gravelly Sand		S2(3)-G1(2)/D
Sand and Boulders		D3
Gravel		G
Fine Gravel		G1
Medium Gravel		G2
Coarse Gravel		G3
Clayey Gravel		D
Silty Gravel		D
Sandy Gravel		G1(2)-S2(3)/D3
Gravel and Boulders		D3
Bedrock		B
Total # of Attributes:	30	20

Table 3.2. Criteria for quality and reliability of data sources used to construct the Glasford model (Modified from Ross et al. 2005).

Rank	Quality	Description	ISGS Data
5	Very high	Complete logs, reports and cores or samples available. Verified location.	Core described by geologist; engineering boring; sample set; with borehole geophysical log collected by geoscience professional.
4	High	One complete log or sample available with driller's report. Verified location.	Borehole geophysical log or sample set collected by driller or technician with complete driller's geologic log.
3	Moderate	Driller's geologic log with no apparent inconsistency with nearby data. Verified location.	Sample set (incomplete) and complete driller's geologic log; sample set or borehole geophysical log with incomplete driller's geologic log.
2	Fair-selected	Selected driller's geologic logs based on quality of descriptions and relative stratigraphic consistency with nearby data ranked from 5-3 for quality. May have verified location.	Driller's geologic log only.
1	Fair-unselected	Unselected driller's logs or poor or/ incomplete geologic logs that do not relate to nearby data. May have verified location.	Driller's geologic log only.
0	Incomplete	Poor or missing description of the geology; not able to verify location.	May or may not have driller's geologic log.

Information from continuous cores was a very important part of the geological modeling process and was key control for the geological framework. These data were needed to constrain hydrofacies assemblages in the Glasford model and were the priniciple data points for creating surfaces (see section 3.3.4). As shown in Table 3.2, continuous cores were interpreted as the highest quality data and all surfaces in the geological model were constrained to hydrofacies boundaries interpreted from these cores (see Appendix C pg. 134 for all high-quality borehole information). In addition to continuous cores, data compiled from engineering borings were also interpreted as the highest quality data, as the engineering logs typically contain very detailed data. Engineering logs include material properties such as standardized material descriptions, moisture content, blow counts and interpretation of depositional processes. Furthermore, most engineering borings are surveyed to locate the boreholes accurately.

Logs of natural gamma radiation were particularly useful to interpret the geologic materials when core recovery was incomplete. When these logs were paired with samples from the drilling operations at intervals taken every 1.5 m (5 ft), a fairly accurate representation of the materials was established. In addition, profiles from near-surface geophysical profiles were also used to identify the upper and lower contacts of the Glasford deglacial unit (see Chapter 2, Figure 2.3 for locations of geophysical surveys in the study area). These profiles differed from the borehole geophysical logs, as they cannot be used to identify material variability within the deglacial unit. Instead, the geophysical data can be used to delineate the extent of the Glasford deglacial unit and major depositional or erosional boundaries (reflectors) in the unit (see Chapter 2, section 2.3.1). The rest of the data especially logs from water-wells were used as supplementary data only. Logs from water-wells were not used to make major decisions about the internal character of the unit. Those records were ranked 2 for data quality, and were used to help determine general trends and constrain surface interpolation between higher quality data (rank 5-3). The logs from water-wells ranked 1-0 contain many errors including: location inaccuracies, poor and varying geologic descriptions (e.g., inconsistent terminology, large spatial variations, etc.) and generalized and missing descriptions. However, many geologic logs from water-wells have no apparent inconsistencies or obvious errors. At the scale of the Glasford model, the selected logs from water-wells were still useful to provide a general idea of the subsurface where no other data were available.

In general, the logs from water-wells were highly clustered throughout the study area. As a result, selection of fair-quality logs from water-wells included a manual declustering approach where one log from a water-well was chosen to represent a 1.6 km^2 (1 mi^2) area coincidental to sections of the Public Land Survey System (PLSS) in Illinois. As outlined in Table 3.2, the selected logs were chosen based on quality of description and consistency with nearby high-quality data. The area where the Glasford model was largely based on lower quality data (rank 2) is identified as high-uncertainty; the selected logs were still inherent to model creation and were used to facilitate interpretations between key data points or in areas where high-quality data were not available.

3.3.2 Hydrostratigraphic Analysis

Geologic data derived from continuous cores include geologic materials, stratification, texture, colour, reactivity, sorting, organics, sedimentary structures, etc. These data were examined carefully in order to identify the main hydrostratigraphic units, bodies and assemblages. Common and genetically related sediments were thus grouped into a package of sediments, which were thought to have been deposited in the same environment or time of deposition (Walker and James 1992). Other assignments were based on published stratigraphic interpretations (e.g., Willman and Frye 1970; Kempton et al. 1991), professional judgment of the geologists working on the project, and key features from differing quality data (i.e., engineering borings, driller's logs, sample sets, and gamma logs) (Stumpf and Dey in press).

For all datasets, important criteria for determining the top of the Glasford deglacial unit and associated Champaign valley included the presence of the overlying Wisconsinan sediments such as: undifferentiated tills of the Wedron Group; and 2) sand and gravel of the Ashmore tongue (see Chapter 2, Figure 2.2). These units are commonly described as pinkish brown to gray clay, or diamicton (Willman and Frye 1970). The Sangamon Geosol was also used to mark the top of the Glasford deglacial unit. The soil horizon was easily identified in continuous cores, as the zone was sometimes leached of carbonates, and in logs from water-wells by the description of green clay, oxidized sediment, and clay accumulation in diamicton and/or sand and gravel. Finally, logs of natural gamma radiation provided insight into the presence of the deglacial unit due to the variability of counts per second (CPS) in the gamma logs, thus demarcating the deglacial unit. The lower contact of the Glasford deglacial unit is the Vandalia Member till, which is a gray, loamy dense diamicton (Willman and Frye 1970), and in the area of the Champaign valley in the Glasford deglacial unit, the till unit was eroded.

The Glasford deglacial unit was further subdivided into hydrofacies bodies and assemblages. The hydrofacies assemblages were first established by analyzing seven continuous cores and their associated geophysical data (see Chapter 2). Analysis of these data along geophysical profiles allowed for the identification of mappable hydrofacies bodies (e.g., the Champaign valley and tabular sediment body, see Chapter 2). The identification of materials in cores aided in grouping sediments into distinct hydrofacies assemblages deposited in either the Champaign valley (i.e., hydrofacies assemblages V1-V3) or forming a tabular body that extends across the study area and overlies the valley (i.e., hydrofacies assemblages A-C). Table 3.3 provides a brief description of hydrofacies assemblages outlined in Chapter 2, which were created to group descriptions of similar lithology and position in the Glasford model (Figure 3.3).

Table 3.3. Classifications used to describe the Glasford deglacial unit.

Hydrofacies Assemblage/ Model Code	Sediment Characteristics
A	Discontinuous highly-compacted diamicton with sandy interbeds.
B	Coarse and/or fine-grained sand with beds of gravel and pebbles.
C	Diamicton with minor beds of sand and gravel and/or silt and clay.
V1	Thick succession of very fine to coarse sand, or gravelly sand.
V2	Silt loam diamicton and laminated and/or massive silt and clay.
V3	Fine to medium sand with some gravel.

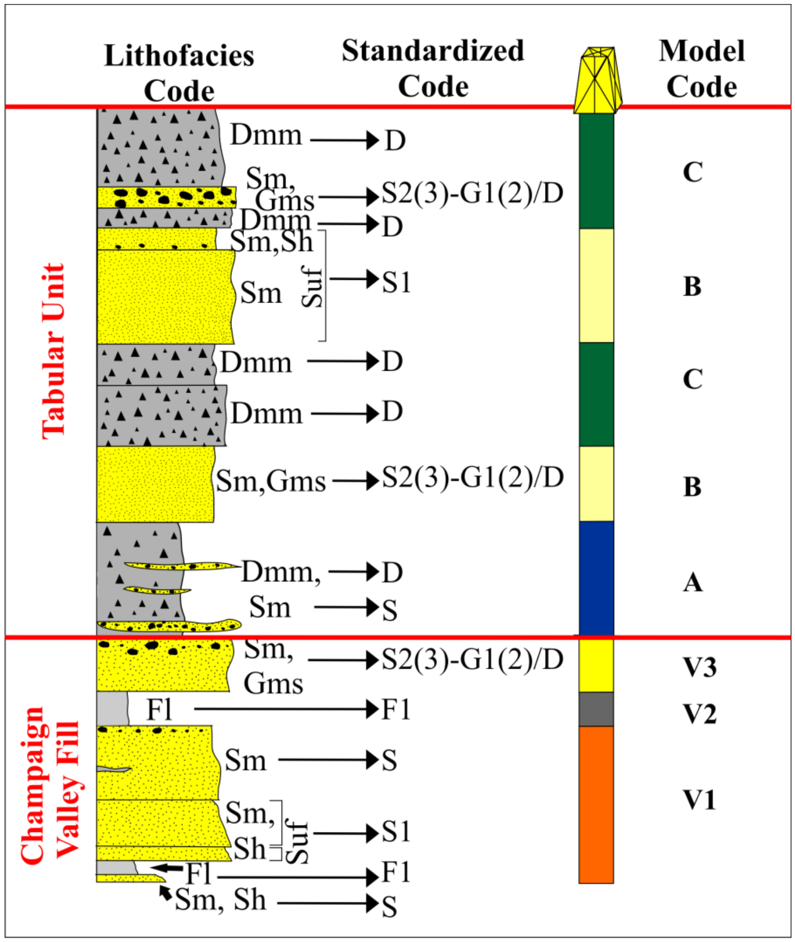

Figure 3.3: Idealized geologic log of the Glasford deglacial unit including identified hydrofacies assemblages. A standardization process conducted using the code system presented in Table 3.1 assisted in grouping the non-standardized lithologic descriptions for logs from water-wells, and provided a standardized scheme for the inclusion of multiple datasets of varying quality (ranked 5-2) to import into the gOcad geomodelling software. The visualization of standardized data in 3-D aided in assigning model codes (Table 3.3) to each data point for subsequent model creation (Modified from Ross et al. 2005).

GIS systems were needed to help prepare the variety of data before it was imported into the 3-D system. Both ESRI® ArcMap™ 9.3 and gOcad® (Paradigm™) 2009.2 were thus used in this study. In ArcMap, hydrofacies assemblages (Table 3.3) were allocated to point data (i.e., well data), and 3-D visualization of well locations, logs, and materials (Table 3.1) was completed in gOcad (Figure 3.3). The point data visualized using gOcad included: 1) location information (e.g., co-ordinates of point location, site elevation, and total depth of studied interval); and 2) hydrofacies assignments (i.e., top surface elevations and model codes, Table 3.3). This approach combined different, and often complimentary, capabilities of GIS and 3-D systems to provide improved conceptualization of the stratigraphy, sedimentology, and geometry of subsurface geologic materials, which is necessary to develop a consistent geological model.

3.3.3 Geological Modeling

A Geological Framework Model (GFM) representing the stratigraphic architecture of the Glasford deglacial unit was first developed for this study (see Chapter 2). Triangulated surfaces were created using gOcad and these surfaces represented the top of the mapped hydrofacies assemblages of the GFM. The surfaces were then used to create a stratigraphic grid (SGRID), which was used to further partition the subsurface materials to classify internal heterogeneity at the scale allowed by data density and resolution. Figure 3.4 shows the general approach of using the GFM as a basis for the gridding process.

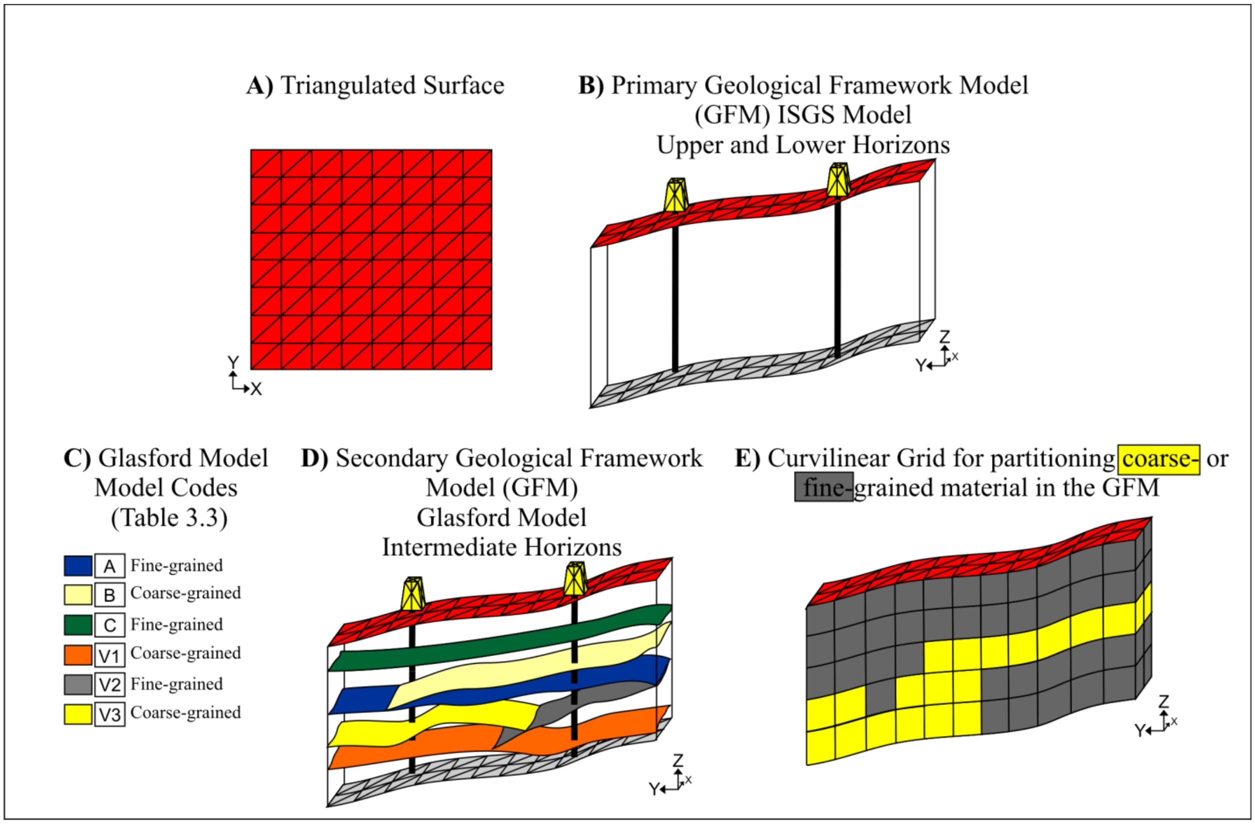

Figure 3.4: The general approach of using a GFM as the repository of the mappable hydrostratigraphic geometry for subsequent 3-D visualization, and for the partitioning of units into grids. Different grids can be developed from the same GFM (i.e., primary or secondary grid) to map internal hydrofacies assemblages depending on the degree of complexity required and resolution of available data (After Ross et al. 2007).

3.3.4 Surface Construction

Surfaces for the Glasford model were created from standardized data points and matched to the elevation of the top of each hydrofacies assemblage (i.e., model codes V1-V3 or A-C, Table 3.3) (Figure 3.4). The surface was then smoothed using the Discrete Smooth Interpolation (DSI) in gOcad (Mallet 1992). This interpolation method uses discrete triangulated surfaces that are interpolated to fit the elevation of model codes (hard constraints) while minimizing a surface roughness criteria as well as any pre-defined ‘soft’ constraints (e.g., minimum and maximum thickness range).

Once the surfaces were interpolated in gOcad, any surfaces that overlapped were edited, to produce a model with the correct succession of hydrofacies assemblages. Nine surfaces were used to model the Glasford deglacial unit (i.e., V1, V2, V3, A, lower B, lower C, upper B, and upper C). These surfaces included each hydrofacies assemblage in Table 3.3, and in some areas assemblages B and C were repeated as another cycle of sediments above (see Chapter 2, sections 2.5.2.2 and 2.5.2.3) (Figures 3.4 C and D). All nine surfaces were modeled to be truncated by surfaces in the ISGS model (i.e., the primary GFM, Figure 3.4 B) including: 1) the upper bounding surface of the Glasford deglacial; 2) the upper bounding surface of the Champaign valley fill; and 3) the lower bounding surface of the Glasford deglacial unit/ Champaign valley fill.

3.3.5 SGRID Modeling

As previously mentioned the Glasford deglacial unit is highly heterogeneous, and as a result a hierarchical model was used for the Glasford model. The hierarchical model was used to represent the upper and lower horizons of the Glasford deglacial unit as the most significant barriers to groundwater flow and further detail of the Glasford deglacial unit was included using a SGRID object built in gOcad to represent depositional heterogeneities within the unit. Hydrofacies assemblages modeled in the SGRID are composed of layers of individual cells. Cells were modeled to match surfaces created to represent point data (Figure 3.4 E). To further characterize depositional heterogeneities within the Glasford deglacial unit, key assemblages of coarse-grained deposits (i.e., sand, and sand and gravel or facies assemblages V1, V3, and B), and fine-grained deposits (i.e., diamicton, silt, and clay or facies assemblages V2, A, and C) were assigned to each of the cells in SGRID such that only coarse- and fine-grained cells were modeled to capture the essential aspects that affect fluid flow in the Glasford deglacial unit (Figure 3.4 E).

3.3.6 Hydraulic Properties

Little is known about the hydraulic properties of the Glasford deglacial unit, because aquifer testing such as slug or pump tests were not conducted, or the data were not available to the author. As a result, preliminary hydraulic conductivity values were determined using empirical formulae based on grain size of bulk samples from sediments examined in Chapter 2. The empirical formulae are often used for the determination of hydraulic conductivities from grain size compositions when in-situ aquifer test data are not available. Six empirical equations were used to calculate hydraulic conductivity of 55 grain size samples and the final results were selected according to the domains of applicability for the formulae and associated samples. The six empirical formulae used are shown in Table 3.4. Additional calculations include information on the total thickness, volume, and porosity estimates for the Glasford deglacial unit. (See Appendix D pg. 143 for porosity values calculated from grain size analyzes conducted and reported in Chapter 3).

Table 3.4: Empirical equations and domains of applicability (After Odong 2007).

Empirical Equation	Formulae	Parameters	Applicability
Equation 1: Kozeny-Carman[1,2,3,5,6]	$K = \frac{g}{v} \times 8.3 \times 10^{-3} \left[\frac{n^3}{(1-n)^2} \right] d_{10}^2$	Most widely accepted (not appropriate for either soils with effective grain size above 3 mm or for clayey soils)	Probably the best estimate for several samples of varying grain size distribution.
Equation 2: Breyer[1,2,6,7]	$K = \frac{g}{v} \times 6 \times 10^{-4} \log \frac{500}{U} d_{10}^2$	Does not consider porosity (therefore defined as 1). Most useful for materials with heterogeneous distributions and poorly-sorted compositions. Uniformity coefficient between 1 to 20 and effective grain size between 0.06 mm and 0.6 mm.	Good method for poorly-sorted materials. Poor estimation for well-sorted materials.
Equation 3: Slitcher [1,2,3,5,7]	$K = \frac{g}{v} \times 1 \times 10^{-2} n^{3.287} d_{10}^2$	Most applicable for grain-size between 0.01-5 mm.	Usually low K derived (considered inaccurate).
Equation 4: Terzaghi[1,2,3,4,5,6]	$K = \frac{g}{v} \cdot C_t \cdot \left(\frac{n - 0.13}{\sqrt[3]{1-n}} \right)^2 d_{10}^2$	Large-grain sand. (Average C used: 8.4×10^{-3}).	Usually low K derived (may be due to the average C used).
Equation 5: Alyamani & Sen[1,6,8]	$K = 1300 \left[I_o + 0.025 (d_{50} - d_{10}) \right]^2$	Poorly-sorted samples. Uses intercept I_o taken directly from grain size distribution.	Best for heterogeneous poorly-sorted samples.
Equation 6: Hazen[1,2,5,6]	$K = \frac{g}{v} \times 6 \times 10^{-4} \left[1 + 10 (n - 0.26) \right] d_{10}^2$	Uniform sands (also useful for fine sand to gravel range).	Less accurate than the Kozeny-Carman method as it is based on the d_{10} (effective diameter) of the grains, rather than the entire particle distribution.

Where:

[1] K= hydraulic conductivity,

[2] g= gravity (9.8 m/s^2),

[3] v= kinematic viscosity; and is related to dynamic viscosity (μ) and the fluid (water) density (ρ) as follows: $v = \frac{\mu}{\rho}$

[4] C or Ct= sorting coefficient; an average C was used for the calculated K-values ($8.4x10^{-3}$). The C-value is: $6.1 \times 10^{-3} < C_t < 10.7 \times 10^{-3}$

[5] $f(n)$= porosity function: different for various empirical equations, and includes:
$n = 0.255(1 + 0.83^U)$

[6] d_e= effective grain size diameter; different for various empirical equations, and includes the d_{10}, $d_{20,}$ and d_{50} taken from Appendix D pg. 143: Grain Size Statistics.

[7] U= coefficient of grain uniformity; where U is related to the d_{60} and d_{10} taken from Appendix D pg. 143: Grain Size Statistics. $U = \left(\frac{d_{60}}{d_{10}}\right)$

[8] I_o= intercept in mm of the line formed between the d_{50} and the d_{10} taken from grain size and associated statistics are found in the digital appendices Appendix B pg. 132. Grain size statistics from the seven continuous cores in Chapter 2 and the Higginsville section are in Appendix D pg. 143.

3.4 Results

Using available data sources and derivative products from the Glasford model, the thickness, extent, and distribution of coarse and/or fine-grained materials have been identified through examination of cross-sections, and an associated block model of the Glasford model. Further analysis of the physical and geometric properties of the Glasford deglacial unit, through the 3-D visualization of borehole geophysical logs in gOcad, provides a preliminary quality check of the geological model when the borehole geophysical logs are compared with arbitrary cross-sections in 3-D. Lastly, estimates of the hydraulic conductivities and potential aquifer and/or aquitard units in the Glasford deglacial unit are provided. The following provides the analyses of the Glasford model, and some examples of how the Glasford model can be used for different hydrogeological applications.

3.4.1 Glasford Model Data

To create the Glasford model a total of 907 data points were used, as summarized in Table 3.5. The total number of data points used was 54.5% of the total data. The remaining 45.5% of the data points contained insufficient geologic data or had locations that could not be verified, and closely-spaced points with similar geologic logs, especially over the MBV where the data point are clustered that were not needed to represent the Glasford deglacial unit (Figure 3.5). Instead, as described in section 3.3.1 one data point was chosen from each section that contained geologic information representative of the area (Figure 3.5). All data, whether used to create the model or not, are included in the project database (see Appendix B pg. 132).

Table 3.5. Distribution of borehole quality classes integrated in the Glasford model.

Quality (cf. Table 3.2)	Number of Boreholes	% of total dataset	% of data used
Very High	65	3.91	7.17
High	35	2.11	3.86
Moderate	8	0.48	0.88
Fair- selected	799	48.07	88.09
Fair- unselected	711	42.78	0
Incomplete	44	2.65	0
Total boreholes used	907	54.5	
Total boreholes	1662	100	

* Highlighted data represent 11.91% of the highest quality data used for geological model construction.

Although logs from water-wells are numerous in the study area, the Glasford model was first built from data points considered to have the highest quality data (e.g., ranked 5-3; Table 3.2) and only loosely constrained by secondary lower quality data (ranked 2). In other words, logs from water-wells were not used to make significant changes in the stratigraphy or unit geometry that would have a dramatic impact on the model output when there was near-by high-quality data. This is especially prevalent over the critical MBV, as there is good distribution of high-quality data points.

In building the Glasford model, the surfaces constructed in gOcad were interpolated to fit the selected data points. As shown in Table 3.5, the very-high, high, and moderate quality data represented 11.91% of the available data points and were used to construct the Glasford Model. This percentage of the data is sufficient to produce a geological model, and lower quality data were used to facilitate interpretations in areas with a limited number of continuous cores, engineering borings, borehole geophysical data, samples sets, and detailed logs from water-wells. Within the MBV the surfaces are better constrained to the highest quality data. However, outside of the bedrock valley the geological model relies on lower quality data (Figure 3.5). The remaining 88.09% of the data is thus interpreted as fair-quality data and these data points were helpful as they facilitated correlations between points of higher quality data.

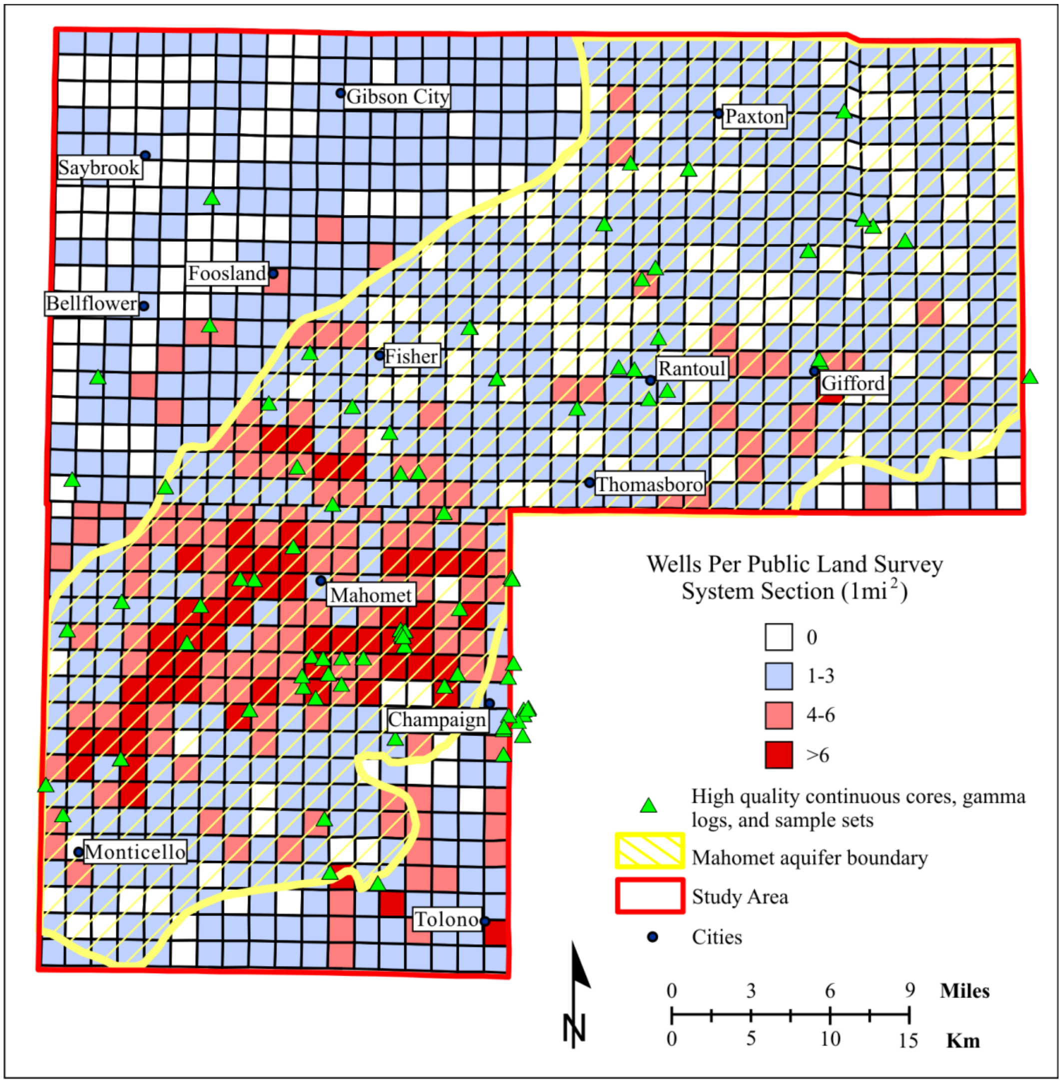

Figure 3.5: Total number of boreholes per section (1.6 km^2 or 1 mi^2) available for examination in the 30 township study area. Boreholes with the higher quality data are located over the MBV.

3.4.2 Glasford model: Thickness, Extent, and Distribution

The Glasford model includes individual hydrofacies bodies and assemblages preserved in the entire hydrostratigraphic unit of the Glasford deglacial unit and are shown with the ISGS model in Figure 3.6. The Glasford model was developed to gain new insights on aquifer and aquitard geometries and their internal heterogeneity represented by the hydrofacies assemblages B, V3, and V1 (deposits of coarse-grained sediment), and assemblages C, A, and V2 (deposits of fine-grained sediments) (Figure 3.6).

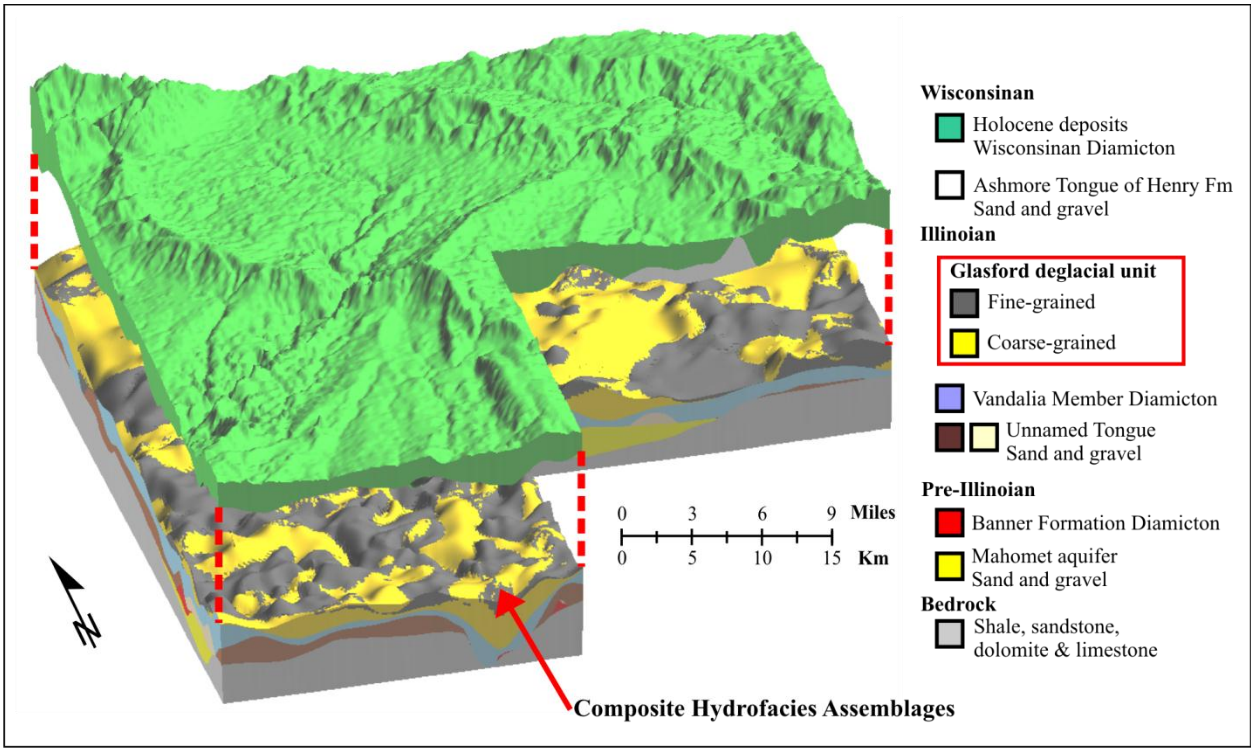

Figure 3.6: View of the geometry of hydrostratigraphic units and hydrofacies assemblages of the Glasford deglacial unit (i.e., V1-V3 and A-C). The 3-D model shown is a combination of the ISGS model and Glasford model. The facies assemblages described in Chapter 2 are shown and represented by either yellow or gray shading representing coarse-grained or fine-grained deposits, respectively. The vertical exaggeration is 25X. See Appendix F pg. 156 for individual cross-sections constructed from the model.

The thickness of the entire Glasford deglacial unit is shown in Figure 3.7 where unit thickness is greatest in the Champaign valley. In this area, the maximum thickness is approximately 70 m (230 ft) and includes hydrofacies assemblages V1-V3 (valley fill) in the valley and assemblages A-C (tabular unit) over the valley (Figure 3.7). Outside of the valley, the deglacial unit is comprised of the tabular unit only, bounded at the bottom by the Vandalia Member till, and has a maximum thickness of approximately 45 m (147 ft). Again, sediments of assemblages A-C are discontinuous across the study area leading to variable thicknesses (Figure 3.7 and Table 3.6).

Individual facies assemblages have also been measured in terms of thickness and volume of the Glasford model. Hydrofacies assemblages of the tabular unit and Champaign valley are shown in Table 3.6. The thickness of the hydrofacies assemblages in the Glasford deglacial unit provides understanding into the geometry of the sediments, which is necessary to locate potential aquifers or sufficiently extensive fine-grained sediments forming important aquitard units. Relatively coarse-grained sand and gravel, specifically units B, V1, and V3 have mean thicknesses for each hydrofacies assemblage of 2-6 m (6-19 ft) and maximum thicknesses of approximately 9 m (29 ft) (Table 3.6) (see Appendix G pg. 161 for thickness data taken from the Glasford model calculated using the gOcad software). Therefore, vertical connections that potentially exist between these different coarse-grained sediment layers in the Glasford deglacial unit could result locally in connected permeable sediments reaching over 20 m (65 ft) in thickness with varying combinations of sand to gravel materials (i.e., vertical sequence of hydrofacies assemblage V1 and V3) forming local aquifers.

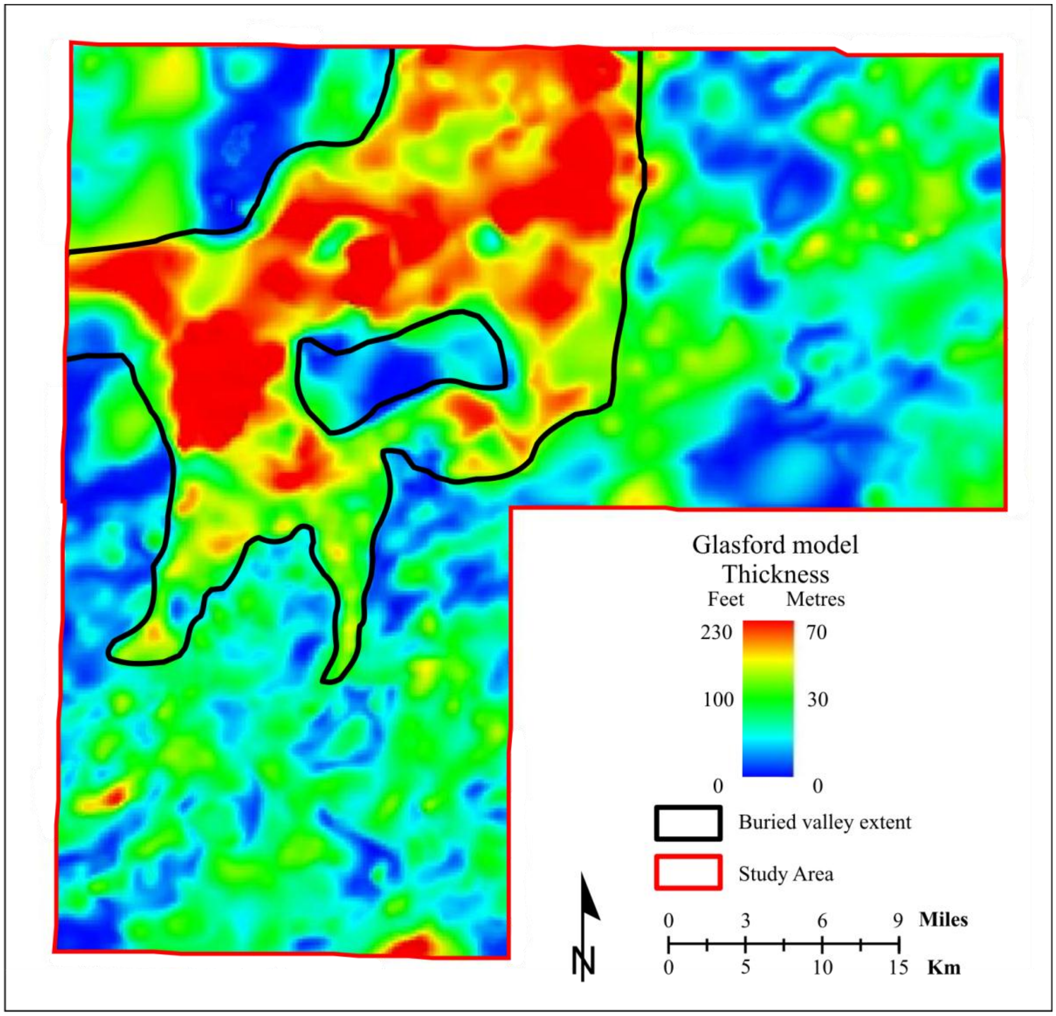

Figure 3.7: Isopach map of Glasford deglacial unit in the study area. The unit is thickest over the Champaign valley and thins dramatically outside of the valley.

The most voluminous body of coarse-grained deposits, which could potentially form one of the most productive aquifers in the study area is located in areas where hydrofacies assemblages V1 and V3 in-fill the Champaign valley and where repeated layers of hydrofacies assemblage B are present in vertical sequence (e.g., significant aquifer thicknesses are highlighted in Figure 3.8). Elsewhere, the layers are thin and discontinuous and may thus not be found in sufficient volume to be considered aquifers, except perhaps where >1.5 m (5 ft) of coarse-grained material could contain water supplies sufficient for domestic uses. Discontinuous units of diamicton and silt and clay preserved in hydrofacies assemblages A, C, and V2 have a mean thickness of 2-5 m (6-16 ft) and a maximum thickness over 15 m (49 ft). However in many areas, layers of silt and clay are relatively thin and do not exceed 3 m (9 ft) in thickness (see Appendix G pg. 161 for thicknesses of units in the Glasford model). Due to the textural variability within diamicton, silt and clay units and their lateral discontinuity, these units may at best offer limited protection to underlying aquifers, and as a result, cannot be considered sufficiently extensive aquitard forming materials.

Table 3.6. Thickness and volume estimates of facies assemblages and associated statistics.

Hydrofacies Assemblage	Thickness (m)				Volume (m^3)
	Median	**Max**	**Mean**	**Std. Dev**	**Gross**
Tabular Unit					
(Upper) C	1.60	8.26	1.85	1.33	$3.93x10^8$
Fine-grained					
(Upper) B	1.86	9.41	2.00	1.46	$9.25x10^8$
Coarse-grained					
(Lower) C	1.96	8.99	2.21	1.48	$1.28x10^9$
Fine-grained					
(Lower) B	2.40	9.00	2.59	1.45	$1.29x10^9$
Coarse-grained					
A	2.37	8.67	2.62	1.76	$9.22x10^8$
Fine-grained					
Champaign valley					
V3	5.01	8.22	5.04	0.93	$6.04x10^7$
Coarse-grained					
V2	4.43	8.62	4.56	1.24	$3.88x10^7$
Fine-grained					
V1	5.35	8.99	5.42	1.10	$7.91x10^8$
Coarse-grained					

*All volumes from the Glasford model were calculated using gOcad. (See Appendix G pg. 161 for mean thicknesses calculated in gOcad).

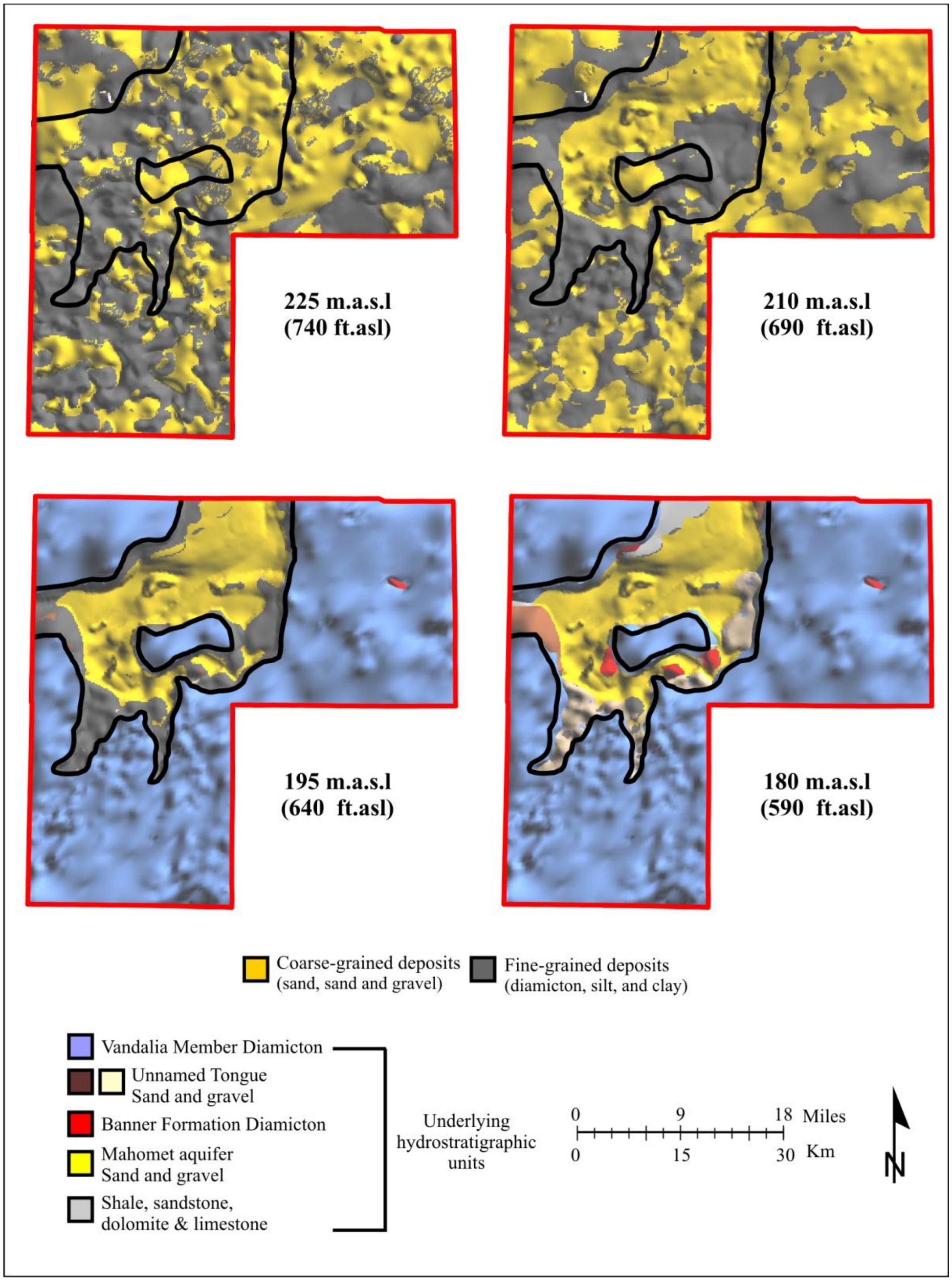

Figure 3.8: Plan views of the Glasford model cut through at different elevations showing the horizontal extent of coarse- and fine-grained sediments (i.e., aquifer and aquitard materials). The areal extent of coarse-grained sediment is located within the Champaign valley (outlined in black). Underlying hydrostratigraphic units (i.e., signified by different colours) are not sliced through and are fixed at the 195 m.a.s.l (640 ft.asl).

Volume estimates of coarse- and fine-grained material were derived from the Glasford model in gOcad. As outlined in Table 3.6 and Table 3.7, the volume of the Glasford model totals 5.70x 10^9 m^3 of the total 2.09x 10^{11} m^3 (Table 3.6) of glacial materials represented in the ISGS model that exist from land surface to bedrock in the study area. The total volume of the model represented by coarse-grained sediments (potentially aquifer materials) is approximately 54% (Table 3.7). Conversely, fine-grained deposits (potentially aquitards materials) represent 46% of the Glasford deglacial unit (Table 3.7). Specifically in the Champaign valley, 95.6% of the materials preserved in the valley are coarse-grained (Figure 3.8; Table 3.7). Overlying the valley in the tabular unit only 46.1% is coarse-grained.

Table 3.7. Total volume and percentages of coarse- and fine-grained sediments in the Glasford deglacial unit and associated features.

	Gross Volume (m^3)	Percentage
Glasford deglacial unit		
Total coarse-grained sediment	$3.06x10^9$	54
Total fine-grained sediment	$2.63x10^9$	46
Total	$5.70x10^9$	100
Champaign valley		
Coarse-grained sediment	$8.51x10^8$	95.6
Fine-grained sediment	$3.88x10^7$	4.4
Total	$8.90x10^8$	
Tabular Unit		
Coarse-grained sediment	$2.21x10^9$	46.1
Fine-grained sediment	$2.59x10^9$	53.9
Total	$4.81x10^9$	100

3.4.3 Hydraulic Properties of the Glasford model

Hydraulic connections may exist between the Mahomet aquifer and coarse-grained sediments in the Glasford deglacial unit due to the presence of the Champaign valley, which was emplaced into the Vandalia Member till, considered a regional aquitard (Wittman Hydro Planning Associates, Inc. 2006). Figure 3.9 provides an example cross-section of the composite Glasford and ISGS geological models showing the more detailed information from the Glasford model and the distribution of coarse-grained sediment in the subsurface above bedrock. The hydraulic connection inferred in Figure 3.9, between coarse-grained sediment assigned to three stratigraphic units (the Ashmore Tongue, Glasford deglacial unit, and the Mahomet aquifer) measures 65 m (213 ft), potentially allowing movement of water between the land surface and the deep aquifers. Figure 3.9 provides a localized example of connections that can exist between sand and gravel in the Glasford deglacial unit and the underlying Mahomet aquifer.

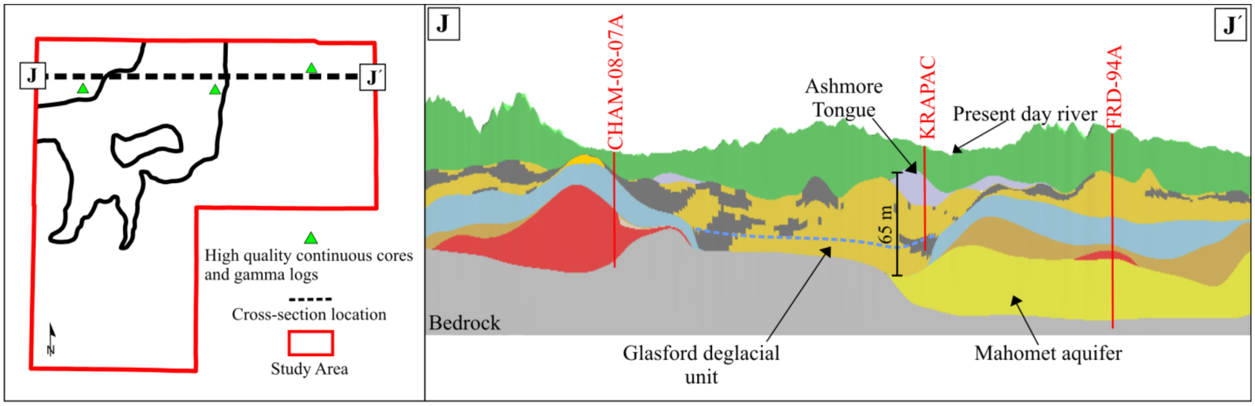

Figure 3.9: Cross-section of sand and gravel material in the Ashmore Tongue (white), Glasford deglacial unit (orange), and the Mahomet Sand Member (light yellow) with a river at the land surface. Aquitard units consist of till (green and light blue) and other fine-grained sediment (gray). The vertical exaggeration of the cross-section is 25X.

Although hydraulic connections may exist between the Glasford deglacial unit and the underlying Mahomet aquifer, locally hydraulic conductivities calculated for sediments within the Glasford deglacial unit vary by orders of magnitude due to different physical characteristics of geologic materials and this could affect the flow of water within the Glasford deglacial unit or to deeper aquifers. Hydraulic conductivities from the hydrofacies assemblages identified in the seven cores examined (see Chapter 2, section 2.5) are shown in Table 3.8. The differences in the calculated hydraulic conductivities show the high level of heterogeneity of the deglacial unit and the limited extrapolation of hydraulic data that can be undertaken throughout the unit.

3.4.4 Borehole Geophysics Applied to Geological Models

Borehole geophysical logs provide in-situ qualitative information about the physical properties of geologic materials surrounding the borehole. For example, logs of natural gamma radiation were particularly useful in defining relative texture of glacial materials (Table 3.9) and supported the identification of hydrofacies assemblages in the Glasford model (Figure 3.10). The natural gamma radiation was measured continuously along the entire borehole with measurements taken every 0.03- 0.06 m (0.1-0.2 ft). Tools available in the gOcad software allowed for quality checking of borehole geophysical data with interpretations of geologic data for multiple wells in the Glasford deglacial unit at once. Cross-sections were constructed to include borehole geophysical data to compare material type represented by the gamma log with coarse- and/or fine-grained materials modeled in the Glasford model.

Table 3.8. Hydraulic conductivities for samples from cores using empirical calculations.

			Hydraulic Conductivity		
Borehole ID and Depth Range	**Facies**	**Material Description**	**m/s**	**ft/s**	**Empirical Formula**
CHAM-08-07A					
30.2-38.7 m (99-127 ft)	A	Diamicton: silt loam; contains beds of sand and gravel	3.85×10^{-8}	1.26×10^{-7}	Kozeny-Carman
CHAM-08-05					
30.2-38.7 m (99-127 ft)	A	Diamicton: silty pebbly; contains beds of sand & gravel	1.03×10^{-8}	3.39×10^{-8}	Kozeny-Carman
Foosland Well					
35.6-36.6 m (117-120 ft)	A	Diamicton: silty, beds of sand, very fine to fine sand	3.85×10^{-8}	1.26×10^{-7}	Kozeny-Carman
36.6-41.2 m (120-135 ft)	V3	Sand & gravel: Fine to medium sand, and gravel	5.41×10^{-7}	1.78×10^{-6}	Kozeny-Carman
41.1-43.3 m (135-142 ft)	V2	Clay: some silt, no clasts	2.77×10^{-8}	9.10×10^{-8}	Breyer
50.6-52.1 m (166-171 ft)	V1	Sand: medium to coarse sand, no gravel	3.19×10^{-4}	1.05×10^{-3}	Kozeny-Carman
FORD-08-01A					
16.8-20.4 m (55-67 ft)	B	Sand & gravel: silty	1.38×10^{-5}	4.53×10^{-5}	Kozeny-Carman
20.4-24.7 m (67-81 ft)	C	Diamicton: sandy; some beds of sand and gravel	1.33×10^{-8}	4.35×10^{-8}	Kozeny-Carman
32.6-35.1 m (107.0-115.0 ft)	B	Sand: coarse, with beds of gravel and some pebbles	1.14×10^{-5}	3.73×10^{-5}	Alyamani & Sen
CHAM-09-07					
10.7-11.6 m (35-38 ft)	B	Sand: Sand with gravel, eluvial clay throughout	8.66×10^{-8}	2.84×10^{-7}	Kozeny-Carman
11.6-13.9 m (38-45.5 ft)	B	Clay: Silt and sand with some gravel, some pebbles	8.08×10^{-8}	2.65×10^{-7}	Breyer
36.6-42.7 m (120-140 ft)	B	Sand: medium to coarse sand with some gravel; minor silt and sand	9.34×10^{-5}	3.06×10^{-4}	Kozeny-Carman
CHAM-07-01A					
30.2-33.5 m (99-110 ft)	B	Sand with silt: medium to fine sand	1.38×10^{-6}	4.53×10^{-6}	Kozeny-Carman
35.1-36.6 m (115-120 ft)	B	Diamicton: silt loam to sandy (large boulder in sequence)	9.26×10^{-9}	3.04×10^{-8}	Kozeny-Carman
42.7-44.8 m (140-147 ft)	B	Sand & gravel: fine to very coarse with beds of gravel	5.17×10^{-4}	1.70×10^{-3}	Kozeny-Carman
CHAM-07-04A					
25.0-31.1 m (82-102 ft)	C	Diamicton: silt loam, sandy, and some pebbles	9.62×10^{-9}	3.16×10^{-8}	Kozeny-Carman
35.4-42.1 m (116-138 ft)	B	Sand: fine to coarse sand; contains beds of pebbly sand	1.64×10^{-5}	5.37×10^{-5}	Breyer
46.9-49.4 m (154-162 ft)	C	Diamicton: silt loam, sandy, and some pebbles	1.06×10^{-8}	3.47×10^{-8}	Kozeny-Carman
49.4-54.7 m (162-179 ft)	B	Sand & silt	3.17×10^{-7}	1.04×10^{-6}	Kozeny-Carman

Table 3.9. Gamma log values used for facies calculator in gOcad (Keys 1997).

Category	Material	Gamma Log Values (CPS)
Coarse-grained	Sand, sand and gravel	0-60
Fine-grained	Diamicton, silt, and clay	60-150

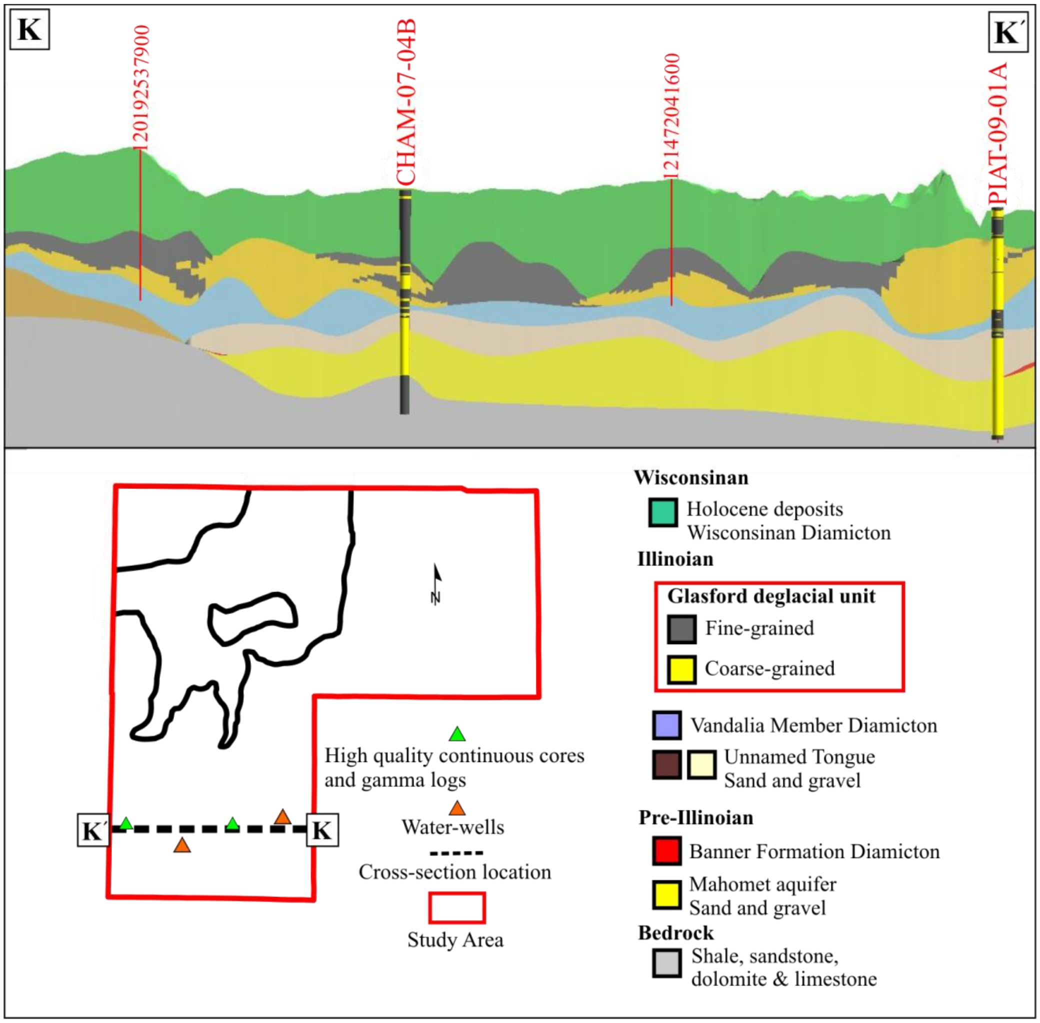

Figure 3.10: Interpolated natural gamma radiation data from two boreholes using the classification system in Table 3.9 shown with a cross-section constructed from the ISGS and Glasford models. In the borehole logs, the coarse-grained sediment is yellow and the fine-grained sediment is gray. The vertical exaggeration of the cross-section is 25 X.

Figure 3.10 shows the values from two boreholes cross-referenced to a cross-section based on the Glasford model. Visual comparisons can be made in 3-D using gOcad's facies calculator that quantifies materials (i.e., coarse- or fine-grained material) generated from user-defined criteria values (Table 3.9) based on properties of gamma logs. In the example shown in Figure 3.10 the material types in the boreholes and model are consistent, which illustrates to some extent, the quality of the model along this cross-section, and the interpretation of material between high quality data points. Further cross sections could be constructed throughout the Glasford model to provide additional checks of the model quality to compare with high quality data points along arbitrary transects.

3.5 Discussion

Sand and gravel deposits of the Glasford Formation were typically described as thin and of limited areal extent (Larson et al. 2003) however, detailed modeling of the Glasford deglacial unit has identified areas where the sand and gravel is >20 m (65 ft). Moreover, potential hydraulic connections may exist between sand and gravel of the Mahomet aquifer and locally significant deposits of sand and gravel in the Glasford deglacial unit. These potential connections are suggested on the basis of the stratigraphic architecture of the Glasford deglacial unit, and hydraulic data would be needed to estimate the importance of these connections. However, subdivision of coarse- and fine-grained sediments in the Glasford deglacial unit provides some indication of the spatial heterogeneity and extent of the aquifer and aquitard forming materials, which may directly affect groundwater flow in the study area.

3.5.1 Determination of the Hydrogeologic Units of the Glasford model

Relatively coarse-grained sand and gravel are considered to be potentially the most productive aquifers in the Glasford deglacial unit. Previous calculations of the Glasford sand include average hydraulic conductivities measured at 2.0×10^{-3} m/s (Kempton et al. 1991). This value is higher than the hydraulic conductivities calculated for the sand and gravel of the Glasford deglacial unit that averaged 4.95×10^{-4} m/s (see Appendix E pg. 146, Table E.2 for average hydraulic conductivity values). However, previous calculations for materials composing the Glasford aquifers included deposits of sand and gravel lying below the Vandalia Member till that now is assigned to the Unnamed tongues of the Pearl Formation (Stumpf and Dey in press). The hydraulic conductivity value calculated for the sand and gravel in the Glasford deglacial unit include hydrofacies assemblages V1, V3, and B.

In some studies, a minimum of 1.5 m (5 ft) of sand and gravel are needed for consideration as a potential aquifer, and greater thicknesses act as further sources of groundwater supplies (Kempton et al. 1982). The sand and gravel of the Glasford deglacial unit is typically 2-6 m (6-19 ft) thick with maximum thicknesses of approximately 9 m (29 ft) (Table 3.6), leading to possible aquifer thicknesses of over 20 m (65 ft) when coarse-grained hydrofacies assemblages are vertically stacked in glacial sequence. Laterally continuous coarse-grained sediment assemblages, primarily located in the Champaign valley, potentially represent local aquifers of limited but usefully productivity for east-central Illinois. These small aquifers consisting of sand and gravel of hydrofacies assemblages V1 and V3 are characterized by hydraulic conductivities ranging from $1.07x10^{-3}$ m/s to $1.78x10^{-6}$ m/s (average hydraulic conductivities calculated from Table 3.8). In contrast, although fine-grained layers and diamicton units (hydrofacies assemblages V2, A, and C) impede fluid flow in the Glasford deglacial unit, they are in fact highly heterogeneous and too discontinuous to be considered aquitards with much integrity. These fine-grained layers and units have an average hydraulic conductivity of $4.38x10^{-8}$ m/s (average hydraulic conductivities calculated from Table 3.8), which is consistent with aquitard-forming materials. However, clearly the discontinuous nature of the fine-grained units and the complexities that exist in the units (e.g., beds of sand and gravel) limit the ability of these materials to act as confining layers for the mitigation of contaminants into groundwater and underlying aquifers (e.g., the Mahomet aquifer).

3.5.2 Hydrogeology Implications

The Glasford model was used to calculate the total coarse- and fine-grained materials in the Glasford deglacial unit. Overall, the unit consists of 54% coarse-grained material and 46% fine-grained material and as a result, the Glasford deglacial unit is a highly heterogeneous body of sediments that is neither an aquifer nor an aquitard in a strict sense (as previously mentioned in section 3.2.1). In some cases, the fine-grained sediments form low-permeability layers within larger heterogeneous aquifer bodies or are found mixed with permeable sediments forming a hybrid body. This type of sediment body is usually found within the tabular unit, and thus this unit challenges the classical subdivision of the subsurface into aquifers and aquitards (Figure 3.11). These highly heterogeneous units could be referred to as hybrid layers consisting of complex assemblages of high permeability and low permeability sediments. Consequently, this concept could be characteristic of some types of ice-contact and/or ice-marginal sediment assemblages that were deposited due to different processes and with highly-variable energy levels (Figure 3.11). On the other hand, the coarse-grained units that in-fill the Champaign valley and have been emplaced into the Vandalia Member till may be identified as discontinuous aquifers as 95.6% of the valley is filled with sand and this could possibly represent aquifer resources in the Glasford deglacial unit or provide pathways to potentially recharge the Mahomet aquifer. Thus, 3-D representation of geologic materials in the Glasford model is extremely important as it may aid scientists to make more accurate predictions about travel times and solute concentrations to significant well fields that penetrate the Mahomet aquifer, and supply numerous municipalities with water.

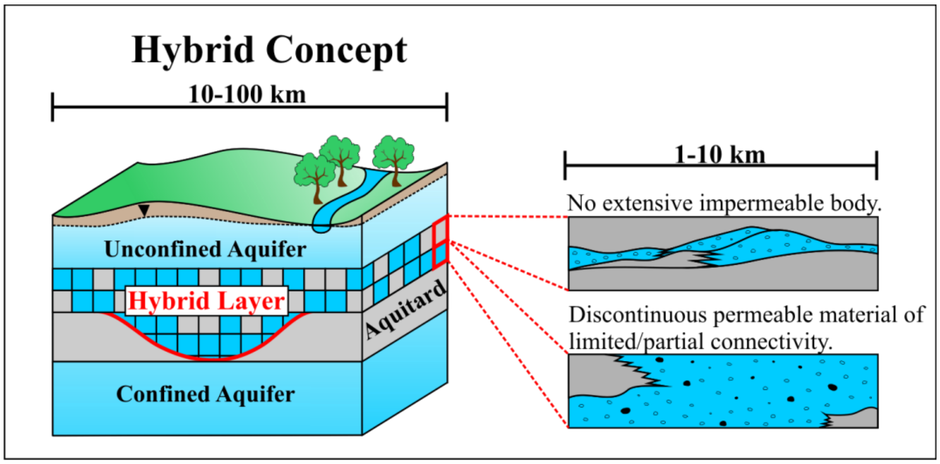

Figure 3.11: Idealized conceptual model of hydrogeologic units, whereby the subsurface is divided into aquifers, aquitards, and hybrid layers of low and high permeability sediments. Hybrid layers are too heterogeneous even at regional scale to fall within the class of aquifer or aquitard. Hybrid layers may better describe, at regional scale, the many depositional elements of the Glasford deglacial unit that do not form mappable aquifer/aquitard units due to their discontinuous nature and highly heterogeneous character, as well as other ice-contact and ice-marginal bodies in the Great Lakes Region and other areas along the southern Laurentide Ice Sheet.

3.5.3 Geostatistical Approximations

Geostatistical approaches to model heterogeneity within hydrostratigraphic units in the subsurface are commonly used in local hydrogeological investigations (e.g., Weissmann and Fogg 1999; Engdahl et al. 2010; Harp and Vesselinov 2010). Various studies have been undertaken that include analyses of groundwater flow systems with the use of lithologic information to describe heterogeneity. At local scales (e.g., few km^2), geostatistical approaches such as the variogram (e.g., Sahin et al. 1998), kriging (e.g., Ouellon et al. 2008), and Markov Chain (e.g., Li 2007) are used to describe spatial characteristics of geologic materials. Characteristics include: continuity, anisotropy, zone of influence, zonality, and trend. Another geostatistical approach that is used includes stochastic processes (e.g., Al-Khalifa et al. 2007).

In several papers on hydrofacies distributions in buried valleys (e.g., Ritzi et al. 1994; Ritzi et al. 2000; Weissmann et al. 2002; Proce et al. 2004), indicator geostatistical methods were used to describe the geological structure of the buried valleys based on borehole logs. These investigations are typically conducted in an area of a few km^2, they generally focus on one depositional process such as those associated with an alluvial fan, delta, or outwash plain. However, in regional (e.g., 1000 km^2) subsurface investigations, the density of data is too low to apply these methods when constructing a geological model (Seifert et al. 2008). In this study, the density of high-quality data in the Champaign valley was indeed considered too low for appropriate and effective use of these geostatistical methods. The size of the study area and the available data only allowed for mapping of the main units with first-order mapping of hydrofacies assemblages. However, the Glasford model contains bounding surfaces and internal hydrofacies assemblage information that could eventually be used as a framework for geostatistical analyses where the data density is considered high enough for further analysis of the spatial heterogeneity, such as the area between the City of Champaign and Village of Mahomet (Figure 3.5). These types of analyses could include: 1) mapping hydrostratigraphic units using the surface-based approach to describe the top units of similar geologic materials (e.g., the ISGS model); and 2) modeling hydrofacies distribution using geostatistical approaches such as indicator kriging or similar variogram-based techniques (Kostic et al. 2005; Ouellon et al. 2008). However, again analyses conducted would have to be on a much smaller scale, rather than at a county-scale; the scale of the Glasford model. Further property modeling using variability of hydraulic conductivity values would identify areas of high- and low-hydraulic conductivity enabling the model to be used to delineate areas of aquifer and non-aquifer material. Thus, smaller modeling areas with a similar structure to the Glasford deglacial unit could potentially provide qualitative information for the interpretation of spatial relationships in deglacial depositional systems and could simulate the heterogeneity based on multiple geostatistical realizations. However, GFMs with a regional scale level of heterogeneity, such as the Glasford model, are a first step in the analysis of the subsurface geology and sediment heterogeneity and provide the basis for future down-scaling analyses, which may include geostatistical mapping of internal heterogeneity at a higher resolution.

3.5.4 Model Uncertainty and Limitations

The compilation of data from various sources and subsequent modeling in 3-D using these data incorporates inherent uncertainties and errors. The process of data management has several sources of error introduced during data collection and the interpretation of geologic data. Uncertainty was introduced in construction of the model for the Glasford deglacial unit from using non-standardized information, geological interpretations made by non-geologists, and integration of recent and old data (Keefer 2007). Uncertainties also exist due to low data density in some areas (Figure 3.12), limited 3-D data, and incomplete descriptions assigned to low-quality data. Human error, especially during database development, natural variability, and measurement error (e.g., error in recording coordinates of the borehole locations) can also affect the accuracy of a model (Culshaw 2005). Uncertainties are also introduced during the simplification process or when assumptions are made during model construction.

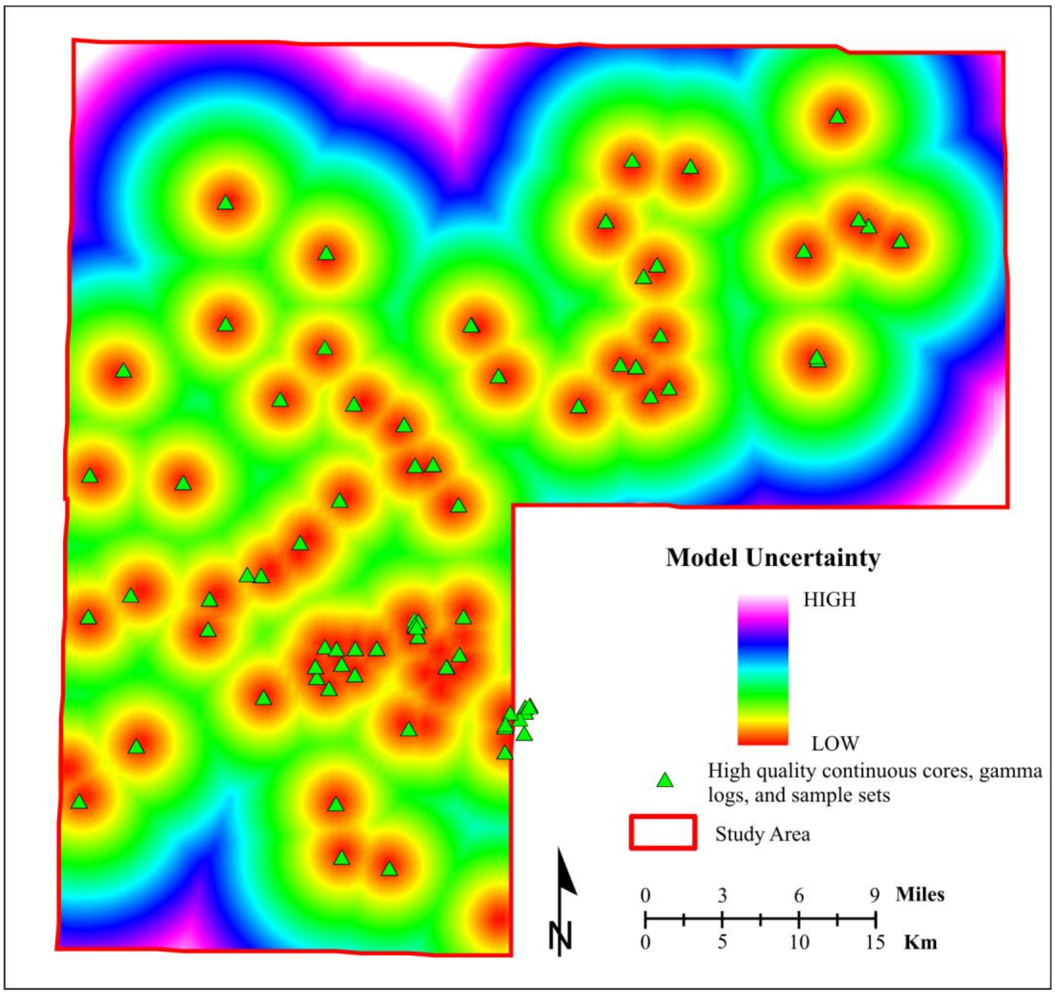

Figure 3.12: Preliminary estimation of uncertainty in the Glasford model calculated by assessing the distance from a well point in gOcad using the SGRID object. The model has the lowest uncertainty in areas constrained by high-quality data points and uncertainty increases with increasing distance from these points.

It is generally considered that uncertainty increases with distance from high-quality data. By considering this simple linear relationship, the Glasford model is better constrained over the MBV, where most high-quality data are located (Figure 3.12). But, there are other factors that affect the degree of uncertainty such as geological complexity and experience of the modeler. More high-quality data are needed to visualize complex geology than where the units are continuous and flat-lying to reach a similar degree of geological model 'robustness'. Therefore, it is difficult to quantify uncertainty in a model because it depends on a number of subjective factors, including the degree of geologic complexity, experience and knowledge of the modeler (Kaufmann and Martin 2008), dimension the data is interpolated (0-D, 1-D, 2-D, 3-D), and distribution of high-quality data. Therefore, measuring uncertainty through measuring the distance from high-quality data is a preliminary estimation of the 'robustness' of the Glasford model; however, as this project was initially developed to improve the characterization of the Mahomet aquifer, the high-quality data distribution is appropriate and well-constrains the model within critical areas.

3.5.5 Modeling Advantages

Significant advances have been made in managing large datasets and analyzing their data. 3-D geomodelling software is now able to process and manipulate large and differing datasets. In the Glasford model, logs from 907 data points (see Table 3.5) were incorporated into gOcad, and subsequent interpolation of surfaces took place with ease. The ability to incorporate numerous data of varying sources in 3-D was advantageous as the 3-D geomodelling environment included formalized procedures to assemble the diverse data sets and incorporate the complex information into one geological model (Robins et al. 2005). Creating the Glasford model with 3-D geomodelling software facilitated the combination of hard-copy data and geologists' interpretation to improve accuracy of the geological model. Similar geomodelling in the future could be assisted by workflow packages available in geomodelling software that provide systematic and routine methodologies for creating 3-D models. This would be especially useful for large organizations that utilize customized workflows and approaches. In addition to creating 3-D geological models, powerful modeling software (e.g., gOcad, Vulcan, Rockworks, Surfer, and Earthvision) produce meaningful models. These software packages are able to generate drift thickness, aquifer vulnerability maps (e.g., Ross et al. 2004), isopach maps and numerous other derivative map products. Derivative map products can be useful for non-geologists to understand geological complexities by providing 3-D visualizations, reports, and interactive displays that does not require specialized training or expertise to read and/or interpret the results (Robins et al. 2005). In addition, visualization of data in this way can be particularly useful when developing the geological framework. From the 3-D representation of datasets, robust framework models can be constructed to act as a platform for additional subsurface investigations. For example, groundwater flow models and maps of vulnerability, geohazard risks, and resource delineation can be developed from 3-D geological models, and exploring and understanding new datasets with the acquisition and discovery of new data, geological models, and applications will only further improve the 3-D representation of the subsurface. But, computer-based geomodelling is only one technique used in successful 3-D mapping of the subsurface. Significant resources still need to be directed toward gathering various types of high-quality data (e.g., continuous cores, 1-D, 2-D, and 3-D geophysical data) in the most critical areas.

3.6 Conclusions

The analysis of the geometry, thickness, and extent of coarse- and fine-grained sediments within the Glasford deglacial unit allowed for the identification of aquifers materials that could potentially hold and transmit water (i.e., hydrofacies assemblages V1, V3, and B) that may contain enough water for domestic uses. However, the study also determined that despite a significant volume of fine-grained sediments representing 46% of the deglacial unit, their distribution is too discontinuous to form aquitard units having a high-degree of integrity. This is evident by the textural variability in hydrofacies assemblages V2, A, and C and the lateral discontinuities of these assemblages. The Glasford deglacial unit is interpreted to contain sediments deposited in ice-contact or ice-marginal depositional environments (see Chapter 2) and it appears that this type of geological setting represents a challenge to the classical aquifer/aquitard delineation concept of the subsurface. Although aquifers in the Champaign valley could be of local significance, most of the Glasford deglacial unit seems to be best described as a hybrid unit consisting of complex assemblages of high permeability and low permeability sediments.

This study highlights the importance of directing resources to characterize the most complex subsurface units as opposed to just focusing on the key regional aquifer units. Consequently, this has allowed for the examination of the implications the Champaign valley system has on potential hydraulic connectivities and the limited protection the deglacial unit provides to the underlying Mahomet aquifer, especially where it fills valleys that emplace the underlying regional aquitard

(Vandalia Member till). In addition, recognizing the limited water resource potential of this shallow, but highly heterogeneous unit highlights the importance of ensuring protection and sustainable development of deeper aquifers such as the Mahomet aquifer. In other words, if the Mahomet aquifer is poorly managed, the Glasford deglacial unit is not likely to provide a solution to water supply issues, nor support the rapid growth in the region.

In summary, 3-D geological modeling is an effective methodology to improve the conceptualization of the stratigraphy, sedimentology, and geometry of subsurface geologic materials and these geological models can be used to develop groundwater flow or contaminant transport models. Consequently, the geological modeling of complex subsurface stratigraphies will improve the understanding of the groundwater flow system in east-central Illinois, and it is likely that these methodologies and techniques can be applied to study the subsurface in other areas of the Laurentide Ice Sheet or where a similar geology is encountered.

Chapter 4

Conclusions

4.1 Modeling the Glasford deglacial unit

Extensive research has been focused on the study of the Mahomet Bedrock Valley (MBV) (e.g., Kempton et al. 1991) as the Mahomet aquifer, which partially in-fills the bedrock valley, is a critical water source in central Illinois. Some preliminary hydrologic and geophysical information (e.g., Mehnert et al. 2004; RWSPC 2009) suggested that the potential for recharge of the Mahomet aquifer is greatest where relatively impermeable layers of diamicton, silt and clay are discontinuous. This study focused on one of those discontinuous buried bodies: the Glasford deglacial unit. From a hydrogeologic point of view, it is a particularly important stratigraphic unit in the glacial sequence of east-central Illinois, as it has the potential to control the flow of water from shallow to deep aquifers in the MBV. This possible control is due to the incision during the Late (deglacial) Illinoian into the underlying Vandalia Member till, a regional aquitard unit, and the textural variability of overlying facies assemblages in the deglacial unit. The coarse saturated sediments of the unit are also locally important for shallow groundwater resources (Kempton et al. 1991). Aquifers of variable extent do occur in the Glasford deglacial unit and are indeed locally important to residents of east-central Illinois, as they supply sufficient water for domestic uses. These groundwater resources are more readily impacted by increased pumping in deeper aquifers, especially when hydraulic connections may be present (Larson et al. 2003).

In this study, a model of the geological materials in the Glasford deglacial unit was developed for a 2642 km^2 (1642 mi^2) study area to improve understanding of the geological record of the unit, its geometry, and internal character, as well as to gain insights into possible aquifer connectivities to the deeper Mahomet aquifer within the MBV. The model is constrained with robust geological and geophysical data including: near-surface geophysics, resistivity surveys, borehole geophysics, and extensive subsurface drilling.

4.2 Thesis Contributions

In this thesis the physical character of the Glasford deglacial unit was described and the stratigraphic architecture and sediment heterogeneity within the unit was modeled. The following are the most significant contributions completed throughout the thesis:

1) The work provided detailed information about the subsurface materials that were used to update the geological framework of the Late Illinoian (Marine Isotope Stage 6 or MIS 6) for east-central Illinois. Detailed vertical descriptions of the examined deposits in continuous cores and outcrops provided important insights into ice-contact and/or ice-marginal environments as recorded in the Glasford deglacial unit. This interpretation can be based on the continuity, texture, and heterogeneity of the unit. The description of the physical character and properties of the sediments that compose the Glasford deglacial unit included: textural and mineralogical characteristics, and associated hydraulic conductivity values.

2) The Glasford deglacial unit is now subdivided into two important architectural elements: the Champaign valley and an overlying tabular unit. These elements were recognized and mapped based on geophysical and borehole data and appear to form key building blocks of the Glasford deglacial unit. The Champaign valley is particularly important because it may significantly impact groundwater flow in the study area. The valley was incised into a regional aquitard, and in some areas may allow for potential hydraulic connections between shallow and deeper aquifers.

3) The assignment of facies in the Glasford deglacial unit provided a refined framework to better describe the unit. The facies identified include: 1) massive, matrix-supported diamicton; 2) interstratified sand and gravel; and 3) massive or laminated fine-grained sediment. These facies were grouped into genetically-related facies assemblages, which were useful to recognize and visualize assemblages of facies preserved in either the Champaign valley (i.e., facies assemblages V1-V3) or the tabular unit (i.e., facies assemblages A-C that extend across the study area and overlie the Champaign valley).

4) The depositional history of the Glasford deglacial unit is interpretated to infer the nature of the deglaciation during the Illinoian stage. The character and heterogeneous nature of sediments in the

unit are typical of ice-contact or ice-marginal environments, and this intepretation is consistent with previous documentation of extensive stagnation during deglaciation in the Illinoian (Stumpf and Dey in press) leading to complex and dynamic processes at the ice margins (Johnson 1976).

5) Preliminary interpretation of the Champaign valley formation in this thesis suggests that a subglacial tunnel valley or proximal subaerial glaciofluvial processes, with progressive valley-fill are the most likely origins for the major architectural element in the study area. The uncertainty is due in part to the difficulty of determining the exact origin of the diamicton preserved in the valley. Better core recovery and detailed examination of internal structures is needed to improve understanding of these diamictons and determine whether they are ice-marginal or subglacial in origin. Another limitation is that the full extent of the valley system has yet to be modeled and its geometry is not well constrained elsewhere with high-quality data. It is thus premature to confirm certain findings that would be diagnostic of subglacial tunnel valley formation such as, for example, a longitudinal undulatory profile (i.e., a valley with overdeepenings). Finally, whether this Champaign valley is associated with ice advance or retreat has yet to be established.

6) The Glasford model facilitated the analysis of the geometry, thickness, and extent of coarse- and fine-grained units. The modeling effort allowed for the identification of possible shallow aquifer units (i.e., hydrofacies assemblages V1, V3, and B) and texturally variable aquitard units (i.e., hydrofacies assemblages V2, A, and C) of variable integrity. Overall, a significant portion of permeable material is located in the Champaign valley as 95.6% of the valley consists of fine- to- coarse sand and gravel. In the overlying tabular unit, sand represents only 53.9% of the total modeled volume.

7) All hydrostratigraphic interpretations and associated model codes have been stored in a Glasford model database to facilitate future geological and hydrogeological studies of the unit. This database could be used as a basis for further analysis of the Glasford deglacial unit at the hydrofacies scale in areas where high-density of detailed data are located. Areas within the Glasford deglacial unit could also be further examined to improve the understanding of the hydraulic connections that may exist between the aquifer units of the Glasford deglacial unit and the underlying Mahomet aquifer.

4.3 Implications of Work

4.3.1 Geological Implications

The land-based glacial history of the Illinoian is much less understood than that of the Wisconsinan as the Illinoian deposits are preserved in only limited areas and are generally buried and thus more challenging to study. One of the best terrestrial records of this time interval exists within the thick Quaternary sediments preserved from land surface to bedrock in Illinois, an excellent setting to study deglaciation events of the Late Illinoian. In addition, the study of the MBV provided a unique opportunity to investigate buried Illinoian deposits in east-central Illinois. This research provides new insights into the processes and deposits of deglacial events in the Illinoian during the latter part of MIS 6. Previously undefined Illinoian deglaciation sediments have been examined and the geological framework of east-central Illinois has been updated to include the Glasford deglacial unit. Overall, this unit is interpreted to record ice-contact and ice-marginal environments and events, although as explained above, uncertainties persist as to the exact origin of some of the facies. Nonetheless, there could be possible geological links with other places in Illinois, as portions of the Glasford deglacial unit could be associated with the 'ridged drift', which has also been interpreted as being of ice-contact and/or ice-marginal origin (Grimley and Philips 2011). As more data are collected from the Glasford deglacial unit, further understanding will be gained about the exact origin of some facies assemblages and regional correlations will be refined.

4.3.2 Hydrogeological Implications

The 3-D modeling of the Glasford deglacial unit is an important case study showing the significance of examining deglacial assemblages of Illinoian-age where they overlie regional aquifers. This study shows that hydraulic connections may exist between the coarse-grained sediments within the Glasford deglacial unit and underlying aquifers of regional importance, despite the presence of an extensive intervening aquitard. This study could also be useful for finding and exploiting relatively shallow groundwater resources in east-central Illinois. Furthermore, this study proposes a new hydrogeologic classification to augment the traditional aquifer/aquitard model. In addition to the classical subdivision of the subsurface into aquifers and aquitards, this thesis proposes to include hybrid layers representing hydrostratigraphic bodies that may not form aquifer or aquitard building blocks at regional scale because of their discontinuous and highly heterogeneous character. These hybrid layers may better represent conceptually the complex ice-marginal deposits that are found across east-central Illinois, and perhaps other similar areas affected by glacial lobe fluctuations during multiple glaciations (e.g., the Great Lakes Region). This new hybrid concept will improve understanding of the geological controls small discontinuous units may have on regional groundwater flow, helps identify areas where the integrity of aquitards is questioned, and lastly, provides an improved hydrogeological model to better understand connectivities between shallow and deep groundwater resources.

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Page range(s):	Vol. 43, No. 5, p.559 & Vol. 43, No. 5, p.627
Translating to:	No Translation
Requested content's publication date:	10/09/2011

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Appendices

APPENDIX A

Descriptions of Continuous Core and Outcrop

The following includes detailed descriptions of the seven continuous cores and one outcrop examined. This information is discussed in Chapter 2. All core descriptions consist of visual analysis of the physical properties of the sediments. Photographs of the described intervals are also included. See digital appendices that contain the detailed descriptions, laboratory data, photographs, natural gamma logs, etc. Selected continuous cores represent a portion of the continuous cores collected as a part of the study of Mahomet aquifer in Champaign County and adjacent areas (see Preface).

Table A.1. Description of core from borehole CHAM-08-05

Top (m)	Bottom (m)	Material	Clast Morphology	Clast Measurements	Roundness
30.2	38.7	Diamicton: silty pebbly; contains beds of sand & gravel; diamicton, loam below 33 m.	Shield: granite or metamorphic clasts equant to prolate, Carbonates: blade, Clastics: chert=equant to blade, siltstone and sandstone: disc to blade.	Medium to Vry Large: M: L=15mm, I=12mm, S=10mm. L: L=25mm, I=20mm, S=12mm, VL: L=60mm, I=45mm, S=35mm.	Roundness: 0.1-0.7 (angular to subrounded) Carbonates are rounded, clastics (e.g., chert) are sub-angular. Sphericity: 0.1-0.7.

Top (m)	Bottom (m)	Texture	Sorting	Lithologies/Percentages	Matrix/Clast Percentages
30.2	38.7	Shield: conchoidal fractures, not as weathered as CHAM-08-07A. Carbonates: rough, weathered surfaces, pitts, broken & angular. Clasts: cherts, smooth & polished, lots of pits, cracks and chips	Poor	Shield= 5, Dolomite=2, Chert=5, Siltstone=2, Sandstone=1.	Matrix-supported silt loam diamicton and ~20% clasts.

		(angular). Sandstones/siltstones: pitted, but smoother surfaces, more polished, but the surfaces are weathered.			

Top (m)	Bottom (m)	Colour	Munsell	Sedimentary Structures	Lithofacies Code	Additional Comments	Model Code
30.2	38.7	Grayish brown	10YR 5/2	N/A	Dmm	Photograph: 101-0225-101-0227	A

* Clast Measurements are made for all pebble sizes and the large (L), intermediate (I), and small (S) axes were measured in millimetres (1 mm= 0.039 inches). Pebble sizes are visually quantified from smallest to largest: granule, S (small), M (medium), L (large), VL (vry large) to cobble sized.
* For sphericity and roundness scales refer to (Boggs 2006).
* Lithofacies code refer to Chapter 2.

Photograph: 101-0225
30.5-33.8 m (100-111 ft)

Photograph: 101-0227
36.9-38.7 m (121-127 ft.)

Photograph: 101-0226
33.8-36.9 m (111-121 ft)

Figure A.1: Core photographs of CHAM-08-05 of the Glasford deglacial unit composed of loamy and stiff diamicton assigned to diamicton facies of facies assemblage A.

Table A.2. Description of core from borehole CHAM-08-07A

Top (m)	Bottom (m)	Material	Clast Morphology	Clast Measurements	Roundness
20.0	22.3	No recovery (diamicton)	N/A	N/A	N/A
22.3	24.1	Diamicton: silt loam; contains beds of sand and gravel	Shield: granite or metamorphic clasts equant to elongate, Carbonates: blade, Clastics: equant to elongate.	Small to large pebbles: S: L=8mnm, I=6mm, S=5mm, M: L=15mm, I=11mm, S=5mm, L: L=26mm, I=20mm, S=15mm	Roundness: 0.1-0.5 (angular to sub-rounded) for all pebbles. Sub-rounded for shield lithologies. Sphericity: 0.3-0.7, mostly 0.3-0.5 as most of the pebbles were not vry spherical.

Top (m)	Bottom (m)	Texture	Sorting	Lithologies/Percentages	Matrix/Clast Percentages
20.0	22.3	N/A	N/A	N/A	N/A
22.3	24.1	Shield: conchoidal fractures very weathered. Carbonates: rough, weathered surfaces, pits, broken & angular. Clasts: chert, smooth & polished, lots of pits, cracks and chips (angular). Sandstones/siltstones: pitted, but smoother surfaces, more polished, but the surfaces are weathered.	Poor	Shield: 2, Dolomite=2, Siltstone=1, Sandstone=2, Chert=5.	Matrix supported silt loam diamicton with ~20% gravel and pebbles.

Top (m)	Bottom (m)	Colour	Munsell	Sedimentary Structures	Lithofacies Code	Additional Comments	Model Code
20.0	22.3	Dark grayish brown	10YR 4/2	N/A	N/A	N/A	N/A
22.3	24.1	Light olive brown (Oxidized)	2.5Y 5/3	N	Dmm	Photographs: 101-0224	A

Photograph: 101-0224
22.9-26.4 m (75-86.5 ft)

Figure A.2: Core photographs of CHAM-08-07A of the Glasford deglacial unit composed of loamy and stiff diamicton assigned to diamicton facies of facies assemblage A with sandy beds towards the bottom of the core.

Table A.3. Description of core from borehole Foosland Well

Top (m)	Bottom (m)	Material	Clast Morphology	Clast Measurements	Roundness
33.8	35.7	Diamicton: silt loam, lots of gravel, some silt, vry fine-medium sand	Carbonates: blade, Chert: Equant (mostly).	Medium to vry large pebbles. M: L=12mm, I=10mm, S=4mm. L: L=30mm, I=15mm S: 4mm. VL: L=45mm, I=30mm, S=15mm	Roundness: 0.3-0.9. Lots of pebbles/cobbles are rounded. Sphericity: 0.3-0.7.
35.7	36.6	Diamicton: silt loam, with beds of sand, some cobbles, vry fine to fine sand	Shield: granite or metamorphic clasts equant to elongate, Carbonates: blade, Equant (mostly), blade, & disc are minor.	Large to cobble sized. L: L=30mm, I=25mm, S=15mm. VL: L=40mm, I=20mm, S=10mm. Cobble: L=70mm, I=55mm, S=30mm.	Roundness: 0.3-0.7, lots of subangular clasts, looks to be broken apart. Sphericity: 0.3-0.9.
36.6	41.1	Sand & Gravel: Fine to medium sand. Fine sand @41-42 m; Gravel @ 36- 37 m.	Carbonates: blade, Equant (mostly). Chert: equant.	Medium pebbles. M: L=20mm,I=15mm,S=10mm.	Clasts: Roundness: 0.3-0.9 subangular to subrounded, some have vry rounded edges. Sphericity: 0.3-0.9.
41.1	43.3	Clay: some silt, no clasts.	N/A	N/A	N/A
43.3	45.7	Sand: silty, vry fine to fine sand, trace gravel @ 43-43.5'.	Grains: equant to disc/prolate	N/A	Grains: Roundness: 0.5-0.9 subrounded to rounded. Sphericity: 0.5-0.9.
45.7	46.3	Sand: fine to medium, no gravel.	Grains: equant to disc/prolate for rock fragments.	N/A	Grains: Roundness: 0.5-0.9 subrounded to rounded. (0.5 roundness for rock fragments). Sphericity: 0.5-0.9.
46.3	46.6	Sand: silty, vry fine to fine sand.	Equant grains.	N/A	Grains: Roundness: 0.3-0.9, RF and F are vry rounded. Quartz can be sub-angular to rounded.
46.6	48.8	Sand: fine to medium sand, no gravel.	Equant grains.	N/A	Grains: Roundness: 0.3-0.9, RF and F are vry rounded. Quartz can be subangular to rounded.

48.8	49.8	Sand: vry fine to fine sand, no gravel.	Equant grains.	N/A	Grains: Roundness: 0.3-0.9, RF and F are vry round. Quartz can be subangular to rounded.
49.8	50.6	Sand: vry fine to medium sand, no gravel.	Equant grains.	N/A	Grains: Roundness: 0.3-0.9, RF and F are vry round. Quartz can be subangular to rounded.
50.6	52.1	Sand: medium to coarse sand, no gravel.	Equant grains.	N/A	Grains: Roundness: 0.3-0.9, RF and F are vry round. Quartz can be subangular to rounded.
52.1	52.4	Sand: vry fine to medium sand, no gravel.	Equant grains.	N/A	Grains: Roundness: 0.3-0.9, RF and F are vry round. Quartz can be subangular to rounded.
52.4	53.0	Sand: vry fine to medium sand, no gravel.	Equant grains.	N/A	Grains: Roundness: 0.3-0.9, RF and F are vry round. Quartz can be subangular to rounded.
53.0	53.9	Clay: some silt, no clasts.	N/A	N/A	N/A
53.9	54.3	Sand: vry fine to fine sand, no gravel.	Equant grains.	N/A	Grains: Roundness: 0.3-0.9, RF and F are vry round. Quartz can be subangular to rounded.

Top (m)	Bottom (m)	Texture	Sorting	Lithologies/Percentages	Matrix/Clast Percentages
33.8	35.7	Chert: smooth, polished surfaces (sub-angular). Clastics: smooth rounded edges with chips.	Moderate to poor	Clasts: Chert= 5, Sandstone=2.	Matrix supported silt loam diamicton, ~49% pebbles.
35.7	36.6	Rough weathered surfaces, smooth polished surfaces, and conchoidal fractures. Same for all pebbles, chert smooth with	Moderate to poor: some very large pebbles.	Clasts: Dolomite=2, Chert=3, Shield=3.	Matrix supported silt loam diamicton, ~10% pebbles.

		chips, sandstones smooth with puts, carbonates have weathered surfaces with pits.			
36.6	41.1	Rough weathered surfaces (carbonates), smooth polished surfaces for both chert and sandstone. Chert have chips, sandstones are pitted. Carbonates are also pitted.	Poor	Clasts: Dolomite=2, Chert=3.	Matrix supported, sand, ~40% gravel.
41.1	43.3	N/A	N/A	N/A	Matrix supported silt and/or clay-rich.
43.3	45.7	Grains: frosted for some quartz. Feldspars had some pits, but were mostly smooth. Quartz: conchoidal fracture. Rock fragments: pitted (slightly more angular).	Well to moderate	Grains: Q=75 (mostly quartz dominate), F=10, RF= 15	Matrix supported sand
45.7	46.3	Grains: frosted for some quartz. Feldspars had some pits, but were mostly smooth. Quartz: conchoidal fracture. Rock fragments: pitted (slightly more angular).	Very Well	Grains: Q= 60, F=30, RF=10	Matrix supported sand
46.3	46.6	Grains: frosted for some quartz. Feldspars had some pits, but were mostly smooth. Quartz: conchoidal fracture. Rock fragments: pitted (slightly more angular).	Very Well	Grains: Q= 60, F=30, RF=10	Matrix supported sand
46.6	48.8	Grains: frosted for some quartz. Feldspars had some pits, but were mostly smooth. Quartz: conchoidal fracture. Rock fragments: pitted (slightly more angular).	Very Well	Grains: Q=85, F=10, RF=5	Matrix supported sand
48.8	49.8	Grains: frosted for some	Very Well	Grains: Q=70, F=10, RF=20	Matrix supported sand

		quartz. Feldspars had some pits, but were mostly smooth. Quartz: conchoidal fracture. Rock fragments: pitted (slightly more angular).			
49.8	50.6	Grains: frosted for some quartz. Feldspars had some pits, but were mostly smooth. Quartz: conchoidal fracture. Rock fragments: pitted (slightly more angular).	Very Well	Grains: Q=60, F=30, RF=10	Matrix supported sand
50.6	52.1	Grains: frosted for some quartz. Feldspars had some pits, but were mostly smooth. Quartz: conchoidal fracture. Rock fragments: pitted (slightly more angular).	Well	Grains: Q=60, F=25, RF=15	Matrix supported sand
52.1	52.4	Grains: frosted for some quartz. Feldspars had some pits, but were mostly smooth. Quartz: conchoidal fracture. Rock fragments: pitted (slightly more angular).	Very Well	Grains: Q=65, F=10, RF=25	Matrix supported sand
52.4	53.0	Grains: frosted for some quartz. Feldspars had some pits, but were mostly smooth. Quartz: conchoidal fracture. Rock fragments: pitted (slightly more angular).	Very Well	Grains: Q=60, F=30, RF=10	Matrix supported sand
53.0	53.9	N/A	N/A	N/A	Matrix supported silt and clay-rich.
53.9	54.3	Grains: frosted for some quartz. Feldspars had some pits, but were mostly smooth. Quartz: conchoidal fracture. Rock fragments: pitted (slightly more angular).	Very Well	Grains: Q=70, F=10, RF=20	Matrix supported sand

Top (m)	Bottom (m)	Colour	Munsell	Sedimentary Structures	Lithofacies Code	Additional Comments	Model Code
33.8	35.7	Grayish brown, slightly oxidized.	2.5Y 5/2	N/A	Dmm	Photograph: 101-0231	V4
35.7	36.6	Grayish brown	10YR 5/2	N/A	Dmm	Photograph: 101-0231	V4
36.6	41.1	Dark grayish brown	10YR 4/2	N/A	Sm/Gms	Photograph: 101-0231	V3
41.1	43.3	Gray	10YR 5/1	Fine laminations	Fl	Photograph: 101-0231	V2
43.3	45.7	Grayish brown	10YR 5/2	N/A	Sm	Photograph. 101-0232	V1
45.7	46.3	Grayish brown	2.5Y 5/2	N/A	Sm	Photograph: 101-0232	V1
46.3	46.6	Olive brown	2.5Y 5/3	N/A	Sm	Photograph: 101-0232	V1
46.6	48.8	Olive brown	2.5Y 5/3	N/A	Sm	Photograph: 101-0232	V1
48.8	49.8	Olive brown	2.5Y 5/3	horizontal laminations to ripples	Sm, Sh	Photograph: 101-0232	V1
49.8	50.6	Olive brown	2.5Y 5/3	horizontal laminations to climbing ripples	Sm, Sh	Photograph: 101-0232 & 101-0233	V1
50.6	52.1	Light olive brown to grayish brown	2.5Y 5/3 to 2.5Y 5/2	N/A	Sm	Photograph: 101-0233	V1
52.1	52.4	Light olive brown	2.5Y 5/3	Ripples	Sm, Sh	Photograph: 101-0233	V1
52.4	53.0	Olive brown	2.5Y 5/3	horizontal laminations to climbing ripples	Sm, Sh	Photograph: 101-0233	V1
53.0	53.9	Gray	10YR 5/1	Fine laminations	Fl	Photograph: 101-0233 & 101-0234	V1
53.9	54.3	Olive brown	2.5Y 5/3	horizontal laminations to ripples	Sm, Sh	Photograph: 101-0234	V1

* Grains percentages are subdivided into Q: quartz, F: feldspars, or RF: rock fragments.

Photograph: 101-0231
33.8-43.3 m (111-142 ft)

Photograph: 101-0232
42.7-50.3 m (140-165.1 ft)

Photograph: 101-0233
50.3-53.4 m (165.1-175.2 ft)

Photograph: 101-0234
53.6-56.7 m (175.9-186.1 ft)

Figure A.3: Facies assemblages V1-V3 preserved in the Champaign valley.

Table A.4. Description of core from borehole FORD-08-01A

Top (m)	Bottom (m)	Material	Clast Morphology	Clast Measurements	Roundness
16.8	20.4	Sand & Gravel: silty	N/A	N/A	N/A
20.4	24.7	Diamicton: sandy; some beds of sand and gravel	Chert: equant to blade, Carbonates; equant to blade, Sandstones and disc to equant.	Granules to vry large pebbles. Granules >4mm, S: L=8mm, I=6mm, S=4mm. M: L=16mm, I=10mm, S=4mm. Large: L=32mm, I=25mm, S=20mm.	Roundness: 0.3-0.7, subangular (chert and carbonates), subrounded (sandstones). Sphericity: 0.3-0.9 (sandstones are equant).
24.7	27.6	Sand: coarse, with beds of gravel and some pebbles	Shield: equant. Chert: equant to blade. Sandstone: disk to equant. Limestone/dolostone: blade/disc.	Granules to large pebbles. Granules <4mm, S: L=8mm, I=4mm, S=3mm, M: L=11,I=10,S=6, L: L=30m, I=25mm, S=15mm.	Clasts: Roundness: 0.3-07 subangular (chert and carbonates) to subrounded (shield and sandstone). Sphericity: 0.3-0.7 most clasts are rounded, but with angular corners etc and thus the subrounded to subangular classification.
27.6	28.2	Sand: fine, with beds of gravel and some pebbles	Shield: equant. Chert: equant to blade. Sandstone: disk to equant. Limestone/dolostone: blade/disc.	Granules to large pebbles. Granules <4mm, S: L=8mm, I=4mm, S=3mm, M: L=11,I=10,S=6, L: L=30m, I=25mm, S=15mm.	Clasts: Roundness: 0.3-07 subangular (chert and carbonates) to subrounded (shield and sandstone). Sphericity: 0.3-0.7 most clasts are rounded, but with angular corners etc and thus the subrounded to subangular classification.
28.2	29.6	Sand: coarse, with beds of gravel and some pebbles	Shield: equant. Chert: equant to blade. Sandstone: disk to equant. Limestone/dolostone: blade/disc.	Granules to large pebbles. Granules <4mm, S: L=8mm, I=4mm, S=3mm, M: L=11,I=10,S=6, L: L=30m, I=25mm, S=15mm.	Clasts: Roundness: 0.3-07 subangular (chert and carbonates) to subrounded (shield and sandstone). Sphericity: 0.3-0.7 most clasts are rounded, but with angular corners etc and thus the subrounded to subangular classification.
29.6	32.6	Sand: fine, with beds of gravel	Shield: equant. Chert:	Granules to large pebbles. Granules	Clasts: Roundness: 0.3-07

		and some pebbles	equant to blade. Sandstone: disk to equant. Limestone/dolostone: blade/disc.	<4mm, S: L=8mm, I=4mm, S=3mm, M: L=11,I=10,S=6, L: L=30m, I=25mm, S=15mm.	subangular (chert and carbonates) to subrounded (shield and sandstone). Sphericity: 0.3-0.7 most clasts are rounded, but with angular corners etc and thus the subrounded to subangular classification.
32.6	35.1	Sand: coarse, with beds of gravel and some pebbles	Shield: equant. Chert: equant to blade. Sandstone: disk to equant. Limestone/dolostone: blade/disc.	Granules to large pebbles. Granules <4mm, S: L=8mm, I=4mm, S=3mm, M: L=11,I=10,S=6, L: L=30m, I=25mm, S=15mm.	Clasts: Roundness: 0.3-07 subangular (chert and carbonates) to subrounded (shield and sandstone). Sphericity: 0.3-0.7 most clasts are rounded, but with angular corners etc and thus the subround to subangular classification.
35.1	36.3	Sand & Gravel: fine to coarse sand	Shield: equant/ prolate. Carbonate: spheroid/blade. Clastic: Chert=equant/disk/blade, Sandstones=equant/disk, blade.	Granules to large pebbles: Granules >4mm, S: L=8mm. I=7mm, S=4mm. M: L=14mm, I=12mm, S=8mm. L: L=22mm, I=15mm, S=10mm.	Clasts: Roundness: 0.3-0.7 subangular (Chert and carbonates) to subrounded (shield and sandstones). Sphericity: 0.3-0.7 some are round at edges i.e., sandstone, others have vry angular edges e.g., chert. Grains: Roundness: 0.3-0.7 subangular (RF) subrounded (Q and F). Sphericity: 0.3-0.9 (Quartz is fairly rounded).

Top (m)	Bottom (m)	Texture	Sorting	Lithologies/Percentages	Matrix/Clast Percentages
16.8	20.4		Poor		Matrix supported sand to silt rich.
20.4	24.7	Rough weathered surfaces, smooth polished surfaces, and conchoidal fractures. Same for	Poor	Clasts: Dolostone=2, Chert=4, Sandstone=2.	Silt-rich matrix supported. Description says sandy, but more silty, with beds of sand

		all pebbles, chert smooth with chips, sandstones smooth with puts, carbonates have weathered surfaces with pits.			and gravel. Sand and gravel approx. 20%.
24.7	27.6	Rough weathered surfaces (carbonates), smooth polished surfaces for both chert and sandstone. Chert have chips, sandstones are pitted. Carbonates are also pitted.	Moderate	Clast: Shield=2, Limestone=1, Dolostone=1, Chert=4, Sandstone=3, Grains; Q=75, F=10 (more feldspar than in most sand facies), RF=15	Matrix supported sand approx. 5% pebbles.
27.6	28.2	Rough weathered surfaces (carbonates), smooth polished surfaces for both chert and sandstone. Chert have chips, sandstones are pitted. Carbonates are also pitted.	Moderate	Clast: Shield=2, Limestone=1, Dolostone=1, Chert=4, Sandstone=3, Grains; Q=75, F=10 (more feldspar than in most sand facies), RF=15	Matrix supported sand approx. 5% pebbles.
28.2	29.6	Rough weathered surfaces (carbonates), smooth polished surfaces for both chert and sandstone. Chert have chips, sandstones are pitted. Carbonates are also pitted.	Moderate	Clast: Shield=2, Limestone=1, Dolostone=1, Chert=4, Sandstone=3, Grains; Q=75, F=10 (more feldspar than in most sand facies), RF=15	Matrix supported sand approx. 10% pebbles.
29.6	32.6	Rough weathered surfaces (carbonates), smooth polished surfaces for both chert and sandstone. Chert have chips, sandstones are pitted. Carbonates are also pitted.	Moderate	Clast: Shield=2, Limestone=1, Dolostone=1, Chert=4, Sandstone=3, Grains; Q=75, F=10 (more feldspar than in most sand facies), RF=15	Matrix supported sand approx. 5% pebbles.
32.6	35.1	Rough weathered surfaces (carbonates), smooth polished surfaces for both chert and sandstone. Chert have chips, sandstones are pitted. Carbonates are also pitted.	Moderate	Clast: Shield=2, Limestone=1, Dolostone=1, Chert=4, Sandstone=3, Grains; Q=75, F=10 (more feldspar than in most sand facies), RF=15	Matrix supported sand approx. 10% pebbles.
35.1	36.3	Rough weathered surfaces (carbonates), smooth polished surfaces for both chert and	Poor	Clasts: Shield=1, Limestone=4, Chert=4, Sandstones =4. Grains: Q=55, F=10, RF=35. Lots of rock	Matrix-supported, 30% gravel/ pebbles

		sandstone. Chert have chips, sandstones are pitted. Carbonates are also pitted.		fragments as they are the granular pebbles in the unit.	
16.8	20.4		Poor		Matrix supported sand to silt rich.

Top (m)	Bottom (m)	Colour	Munsell	Sedimentary Structures	Lithofacies Code	Additional Comments	Model Code
16.8	20.4	Olive yellow	2.5Y 6/6	N/A	Sm, Gms	Photograph: 101-0211	B
20.4	24.7	Grayish brown	10YR 5/2	N/A	Dmm, Sm	Photograph: 101-0215 (Silt-rich diamicton) and Photograph: 101-0211	C
24.7	27.6	Brown	10YR 5/3	Horizontal laminations/ bedding	Sm, Gms to Sh	Photograph: 101-0216 (Just sand), 101-0211 & 101-0212	B
27.6	28.2	Brown	10YR 5/3	Horizontal laminations/ bedding	Sm, Gms to Sh	Photograph. 101-0212	B
28.2	29.6	Brown	10YR 5/3	Horizontal laminations/ bedding	Sm/Gms to Sh	Photograph. 101-0212	B
29.6	32.6	Brown	10YR 5/3	Horizontal laminations/ bedding	Sm/Gms to Sh	Photograph. 101-0212	B
32.6	35.1	Brown	10YR 5/3	Horizontal laminations/ bedding	Sm/Gms to Sh	Photograph. 101-0212	B
35.1	36.3	Brown to grayish brown	10YR 5/3 to 10 YR 5/2	N/A	Sm, Gms	Photograph. 101-0217 (Sand & gravel facies), Photograph. 101-0212, & Photograph. 101-0213	B

Photograph: 101-0211
16.8-27.6 m (55-90.5 ft)

Photograph: 101-0213
35.1-36.3 m (115.5-119 ft)

Photograph: 101-0212
27.6-35.1 m (90.5-115.5 ft)

Figure A.4: Core photographs of FORD-08-01A of the Glasford deglacial unit where there is a repetition of facies assemblage B.

Table A.5. Description of core from borehole CHAM-09-07

Top (m)	Bottom (m)	Material	Clast Morphology	Clast Measurements	Roundness
10.7	11.6	Sand: Sand with gravel, eluvial clay throughout	Small to large pebbles. Limestone, chert, dolostone, and sandstone	N/A	Subangular to round. Rock fragments are angular
11.6	14.5	Clay: Silt and sand with gravel, some pebbles	Medium to vry large pebbles: Shield clasts are blade (elongate to prolate), Chert: equant to blade, Limestone: equant, Sandstone: disc	Medium: L=12mm, I=10mm, S=6mm, Large: L=22mm, I=15mm, S=10mm, Vry Large: L=40mm, I=25mm, S=12mm	Roundness: 0.1-0.7- Angular to subrounded, shield/sandstone/limestone are subrounded. Sphericity: 0.3-0.9, Chert: not vry round, other clasts are fairly rounded, some are still angular
14.5	17.2	Sand & Gravel: medium to coarse sand with some silt; beds of pebbly gravel at 15 & 17 m	Equant to prolate	Small to vry large pebbles	Roundness: 0.3-0.7 subangular to subrounded, Chert not vry rounded, shield/sandstone subrounded. Sphericity: 0.3-0.7 for all clasts. Sandstone 0.3-0.9 roundness subangular to subrounded with a Sphericity of 0.3-0.9.
17.2	17.5	Sand & Gravel: fine sand	N/A	Granules.	Sand: 0.3-0.9 subangular to rounded, especially quartz. F: rounded, RF: subangular to rounded. Sphericity: 0.3-0.9
17.5	18.7	Sand & Gravel: medium to coarse sand with some silt, some pebbles.	Equant to prolate	Small to vry large pebbles	Roundness: 0.3-0.7 subangular to subrounded, Chert not vry rounded, shield/sandstone subrounded. Sphericity: 0.3-0.7 for all clasts. Sand= 0.3-0.9 roundness subangular to subrounded with a Sphericity of 0.3-0.9.

18.7	22.9	Gravel: pebbly (cemented)	Equant to rod	Granules to vry large.	Roundness: 0.3-0.9, subangular to rounded, Sphericity: 0.3-0.9 some clasts are fairly rounded.
22.9	25.7	Sand & Gravel: medium to coarse sand; some beds of gravelly sand, (fining upward sequence)	Equant to prolate	Small to vry large pebbles	Roundness: 0.3-0.7 subangular to subrounded, Chert not vry rounded, shield/sandstone subrounded. Sphericity: 0.3-0.7 for all clasts. Sand= 0.3-0.9 roundness subangular to subrounded with a Sphericity of 0.3-0.9.
25.7	27.4	Gravel: pebbly (cemented)	Equant to rod	Granules to vry large.	Roundness: 0.3-0.9, subangular to rounded, Sphericity: 0.3-0.9 some clasts are fairly rounded.
27.4	30.5	Sand: fine to medium, with some medium to coarse sand.	Equant	Granules to medium pebbles. Small: L=10mm, I=6mm, S=5mm, Medium: L=13mm, I=10mm, S=7mm	Roundness: Clasts: 0.3-0.9 subangular to rounded. Sphericity: 0.3-0.9 fairly rounded. Sand: sub-angular to rounded.
30.5	42.7	Sand: medium to coarse sand with some gravel; minor silt and fine sand	All clasts are equant/ cubic, slightly rod (elongate)	Small to large pebbles. Small: L=8mm, I=7mm, S=6mm, Medium: L=13mm, I=10mm, S=8mm, Large: L=30mm, I=22mm, S=10mm.	Clasts: Roundness= 0.3-0.7, subangular to subrounded, chert/shield are subangular, sandstone subrounded. Sphericity, 0.3-0.7 for all clasts. Sand: Roundness=0.3-0.9 subangular RF and rounded Q and F. Sphericity= 0.3-0.9, some Q are vry equant.
42.7	44.2	Sand & Gravel: some pebbles and silt.	Equant to prolate	Small to vry large pebbles	Roundness: 0.3-0.7 subangular to subrounded, Chert not vry rounded, shield/sandstone subrounded. Sphericity: 0.3-0.7 for all

					clasts. Sand= 0.3-0.9 roundness subangular to subrounded with a Sphericity of 0.3-0.9.
44.2	44.8	Sand & Gravel: medium to coarse sand; some silt	N/A	N/A	N/A

Top (m)	Bottom (m)	Texture	Sorting	Lithologies/Percentages	Matrix/Clast Percentages
10.7	11.6	Pitted, chipped, weathered, quartz looks polished with conchoidal fractures	Poor: lots of sand, but small to large pebbles	Sand: Q=88, F=2, RF= 10.	Matrix supported, ~15% consist of clasts and pebbles
11.6	14.5	Rough weathered surfaces on limestone, polished chert surfaces but with lots of cracks, Sandstone smooth but with pits and chips, Shale very weathered with smooth surfaces with lots of chips, Shield are weathered and have rounded surfaces with pits and chips.	Moderate to well	5% of the unit is clasts. Shield: 2, Shale= 1, Chert=3, Sandstone=2	Matrix supported, clay-rich, ~5% clasts
14.5	17.2	Very weathered looking on surfaces chipped on polished chert surfaces. Sandstones are smooth with chips/pits. Shield rough and weathered looking surfaces. Sand has conchoidal fractures, quartz have polished surfaces with pits and cracks.	Poor: sand and pebbles	Clasts: Shield=3, Siltstone=1, Sandstone=4, Chert=8, Sand: Q=88, F=2, RF=10.	Matrix supported (sand), ~5% pebbles and clasts
17.2	17.5	Conchoidal fracture. Smooth polished surfaces that are pitted and chipped, RF: chipped and broken giving the angular appearance.	Moderate to well	Sand: Q=92, F=3, RF=5	Matrix supported, sand-rich with >1% gravel mostly at the bottom.
17.5	18.7	Very weathered looking on surfaces chipped on polished	Very poor	Clasts: Shield=3, Siltstone=1, Sandstone=4, Chert=8, Sand: Q=88,	Matrix supported (sand), ~15% pebbles and clasts

		chert surfaces. Sandstones are smooth with chips/pits. Shield rough and weathered looking surfaces. Sand has conchoidal fractures, quartz have polished surfaces with pits and cracks.		F=2, RF=10.	
18.7	22.9	Rough weathered surfaces, pitted and chipped on limestone, dolostone etc. Chert look polished but chipped, sandstones etc. look polished with chips and pits.	Very poor	Regular lithologies (no pebble count as it was cemented). Chert, shield, limestone/dolostone, and sandstone dominate.	Clast-support
22.9	25.7	Very weathered looking on surfaces chipped on polished chert surfaces. Sandstones are smooth with chips/pits. Shield rough and weathered looking surfaces. Sand has conchoidal fractures, quartz have polished surfaces with pits and cracks.	Poor	Clasts: Shield=3, Siltstone=1, Sandstone=4, Chert=8, Sand: Q=88, F=2, RF=10.	Matrix supported (sand), ~5% pebbles and clasts
25.7	27.4	Rough weathered surfaces, pitted and chipped on limestone, dolostone etc. Chert look polished but chipped, sandstones etc. look polished with chips and pits.	Very poor	Regular lithologies (no pebble count as it was cemented). Chert, shield, limestone/dolostone, and sandstone dominate.	Clast-support
27.4	30.5	Weathered. Conchoidal fracture. Smooth polished surfaces that are pitted and chipped, RF: chipped and broken giving the angular appearance.	Moderate	Clasts: Chert, sandstone, limestone/dolostone. Sand: Q=75, F=10, RF=15.	Matrix-supported sand. ~>1% gravel
30.5	42.7	Rough weathered surfaces (sandstones), smooth polished surfaces (chert), conchoidal fractures. Chips on the chert and sandstones are vry	Moderate to well	Sand: Q=75, F=10, RF=5. Clasts: Chert=1, Shield=2, Sandstone=1	Matrix-supported, sand-rich, ~5% gravel throughout.

		polished with some pits.			
42.7	44.2	Very weathered looking on surfaces chipped on polished chert surfaces. Sandstones are smooth with chips/pits. Shield rough and weathered looking surfaces. Sand has conchoidal fractures, quartz have polished surfaces with pits and cracks.	Poor: sand and pebbles	Clasts: Shield=3, Siltstone=1, Sandstone=4, Chert=8, Sand: Q=88, F=2, RF=10.	Matrix supported (sand), ~0-20% pebbles and clasts
44.2	44.8	N/A	Poor	N/A	N/A
10.7	11.6	Pitted, chipped, weathered, quartz looks polished with conchoidal fractures	Poor: lots of sand, but small to large pebbles	Sand: Q=88, F=2, RF= 10.	Matrix supported, ~15% consist of clasts and pebbles

Top (m)	Bottom (m)	Colour	Munsell	Sedimentary Structures	Lithofacies Code	Additional Comments	Model Code
10.7	11.6	Olive brown, olive gray	2.5Y 4/3 to 5Y 4/2	N/A	Sm/Gms	Photographs taken in Aug'09	B
11.6	14.5	Leached/oxidized colour, olive gray	5Y 4/2	N/A	Fm/Gms	Photographs taken in Aug'09	B
14.5	17.2	Yellowish brown	10YR 5/4	N/A	Sm/Gms	Photographs taken in Aug'09	B
17.2	17.5	Yellowish brown	10YR 5/4	N/A	Sm	Photographs taken in Aug'09	B
17.5	18.7	Yellowish brown	10YR 5/4	N/A	Sm/Gms	Photographs taken in Aug'09	B
18.7	22.9	Gray	10YR 5/1	N/A	Gm	Photographs taken in Aug'09	B
22.9	25.7	Yellowish brown to brown	10YR 5/4 to 10YR 5/3	N/A	Sm/Gms	Photographs taken in Aug'09	B
25.7	27.4	Gray	10YR 5/1	N/A	Gm	Photographs taken in Aug'09	B
27.4	30.5	Yellowish brown to brown	10YR 5/4 to 10YR 5/3	Bedded	Sm/ Sh	Photographs taken in Aug'09	B

30.5	42.7	Brown	10YR 5/3	Bedded/ horizontal	Sm/Sh	Photographs taken in Aug'09 and Photograph: 101-0207	B
42.7	44.2	Yellowish brown	10YR 5/4	N/A	Sm/Gms	Photographs taken in Aug'09	B
44.2	44.8	Grayish brown	10YR 5/2	N/A	Sm/Gms	Photographs taken in Aug'09	B

Photograph: 7.0-14.0 m (23-46 ft)

Photograph: 14.0-18.0 m (46.59 ft)

Photograph: 18.0-30.5 m (59-100ft)

Photograph: 30.5-36.3 m (100-119 ft)

Photograph: 36.3-40.5 m (119-133 ft)

Photograph: 40.5-46.3 m (133-152 ft)

Figure A.5: Core photographs of CHAM-09-07. This core consists of sediments that are entirely assigned to facies assemblage B. As shown on the EER profile in Chapter 2 (Figure 2.10) a buried channel incises underlying sediments and significant thicknesses of sand and gravel are preserved in the channel.

Table A.6. Description of core from borehole CHAM-07-01A

Top (m)	Bottom (m)	Material	Clast Morphology	Clast Measurements	Roundness
26.2	27.7	Diamicton	N/A	N/A	N/A
27.7	30.2	Sand or Diamicton	N/A	N/A	N/A
30.2	33.5	Sand with silt: medium to fine sand	N/A	N/A	Grains: Roundness: 0.1-0.7 (angular to subrounded for quartz and rock fragments). 0.8 (rounded for feldspars)
33.5	35.1	Sand with silt: with beds of sandy diamicton @ 34 m	Equant and prolate.	Granules to medium pebbles. Granules <4mm, S: L=7mm, I=5mm, S=4mm, M: L=11, I=9, S=5.	Clasts: Roundness: 0.3-0.7 (subangular to subrounded). Sphericity: 0.3-0.7 (some of the pebbles are fairly equant)
35.1	36.6	Diamicton: silt loam to sandy (large granite boulder at bottom of sequence)	Equant and prolate some of the sandstones have a disc appearance.	Granules to large pebbles and large boulder at the bottom of the sequence. Granules <4mm, S: L=9mm, I=6mm, S=4mm, M: L=13,I=8,S=7, L: L=29m, I=22mm, S=16mm.	Clasts: Roundness: 0.3-0.7 (subangular to subrounded). Sphericity: 0.3-0.7.
36.6	47.5	Sand & Gravel: interbedded fine to coarse sand and gravel from 36.5-39.6 m, fine to very coarse with beds of gravel from 42-44 m; fine sand from 44-47.5 m	Shield: equant. Chert: equant to blade. Sandstone: disk to equant. Limestone/dolostone: blade/disc.	Granules to large pebbles. Granules <4mm, S: L=8mm, I=4mm, S=3mm, M: L=11,I=10,S=6, L: L=30m, I=25mm, S=15mm.	Clasts: Roundness: 0.3-0.7 (subangular to subrounded). Sphericity: 0.3-0.7.
47.5	51.2	Sand & Gravel: pebbly, medium to very coarse sand, more pebbles at the bottom	Shield: equant. Chert: equant to blade. Sandstone: disk to equant. Limestone/dolostone: blade/disc.	Granules to large pebbles. Granules <4mm, S: L=12mm, I=6mm, S=4mm, M: L=14,I=8,S=5, L: L=30m, I=26mm, S=17mm.	Clasts: Roundness: 0.5-0.7 (subangular to rounded). Sphericity: 0.3-0.7.

Top (m)	Bottom (m)	Texture	Sorting	Lithologies/Percentages	Matrix/Clast Percentages
26.2	27.7	N/A	N/A	N/A	N/A
27.7	30.2	N/A	N/A	N/A	N/A
30.2	33.5	N/A	Well	Grains: Q=70, F=10, RF=20.	Matrix supported sand. No granules.
33.5	35.1	Grains: Rough weathered surfaces, smooth polished surfaces for both chert and sandstone. Mostly chipped surfaces.	Moderate to well	Clast: Shield, Limestone, Dolostone, Chert, Sandstone.	Matrix supported sand approx. >1% pebbles. Gradual grade into silt.
35.1	36.6	Rough weathered surfaces (carbonates), smooth polished surfaces for both chert and sandstone. Chert have chips, sandstones are pitted. Carbonates are also pitted.	Moderate	Clasts: Shield (granite boulder) and some shield pebbles. Limestone and dolomite, chert and sandstones.	Matrix supported sand-rich diamicton with approx. 10% pebbles.
36.6	47.5	Rough weathered surfaces (carbonates), smooth polished surfaces for both chert and sandstone. Chert have chips, sandstones are pitted. Carbonates are also pitted.	Well: for 39-42.6 m and 44.8-47.5 m. MODERATE: for the rest of the sequence.	Clast: Shield, Limestone, Dolostone, Chert, Sandstone.	Matrix supported sand and gravel approx. 5-10% pebbles.
47.5	51.2	Rough weathered surfaces (carbonates), smooth polished surfaces for both chert and sandstone. Chert have chips, sandstones are pitted. Carbonates are also pitted.	Moderate to poor	Clast: Shield, Limestone, Dolostone, Chert, Sandstone.	Matrix supported sand and gravel approx. 10% pebbles.

Top (m)	Bottom (m)	Colour	Munsell	Sedimentary Structures	Lithofacies Code	Additional Comments	Model Code
26.2	27.7	N/A	N/A	N/A	N/A	Photograph:101-0240	A
27.7	30.2	N/A	N/A	N/A	N/A	N/A	A
30.2	33.5	Yellowish brown	10YR 5/4	Horizontal laminations/ bedding	Sm	Photograph:101-0240	B
33.5	35.1	Brown	10YR 5/3	Beds of diamicton	Sm, Fm, Dmm	Photograph:101-0240 & Photograph: 101-0241	B
35.1	36.6	Grayish brown to grayish brown	2.5YR 5/2 to 10YR 5/2	N/A0	Dmm	Photograph:101-0242	B
36.6	47.5	Brown to yellowish brown (oxidized)	10YR 5/3 to 10YR 5/4	Horizontal laminations/ bedded	Sm/Gms to Sh	Photograph: 101-0242 & Photograph: 101-0243. Some beds containing wood, plant material, and insect body parts from 39-42 m.	B
47.5	51.2	Brown to yellowish brown	10YR 5/3 to 10YR 5/4	N/A	Gms, Sm	Photograph: 101-0243	B

Photograph: 101-0240
22.7-34.8 m (74.5-114 ft)

Photograph: 101-0242
41.6-47.1 m (136.5-154.4 ft)

Photograph: 101-0241
34.8-41.6 m (114-136.5 ft)

Photograph: 101-0243
47.1-52.6 m (154.4-172.5 ft)

Figure A.6: Core photographs of CHAM-07-01A of the Glasford deglacial unit composed of facies assemblage C and B.

Table A.7. Description of core from borehole CHAM-07-04A

Top (m)	Bottom (m)	Material	Clast Morphology	Clast Measurements	Roundness
25.0	31.1	Diamicton: silt loam; some pebbles; very fine to fine sand with gravel from 25.9-26.6 m'.	Chert: equant to blade, Carbonates; equant to blade, Sandstones and disc to equant.	Small to medium pebbles. S: L=8mm, I=4mm, S=3mm, M: L=11,I=10,S=6	Clasts: Roundness/ Sphericity: 0.3-0.7. Subangular to subrounded.
31.1	32.6	Sand & Gravel: silty	Chert: equant to blade, Carbonates; equant to blade, Sandstones and disc to equant. Shield are rounded.	Granules to medium. Granules >4mm, S: L=8mm, I=6mm, S=4mm. M: L=16mm, I=10mm, S=4mm.	Roundness: 0.3-0.7, subangular (chert and carbonates), subrounded (sandstones). Sphericity: 0.3-0.7 (some clasts are fairly equant).
32.6	34.1	Diamicton: Silt loam	Chert: equant to blade, Carbonates; equant to blade, Sandstones and disc to equant.	Small to medium pebbles. S: L=8mm, I=4mm, S=3mm, M: L=11,I=10,S=6	Clasts: Roundness/ Sphericity: 0.3-0.7. Subangular to subrounded.
34.1	35.4	Sand: very fine to fine, with silt and gravel beds @ 35 m	Equant pebbles.	Granules to small pebbles. Granules <4mm, S: L=8mm, I=4mm, S=3mm.	Clasts: Roundness: 0.5-0.9 subrounded to rounded (all clasts). Sphericity: 0.5-0.9 most clasts are rounded. Some pebbles are quite rounded.
35.4	42.1	Sand: fine to coarse sand; contains beds of pebbly sand and gravel	Chert: equant to blade, Carbonates; equant to blade, Sandstones and disc to equant.	Granules to medium. Granules >4mm, S: L=10mm, I=5mm, S=4mm. M: L=15mm, I=9mm, S=3mm.	Clasts: Roundness: 0.3-0.9 subangular (chert and carbonates) to rounded (sandstone). Sphericity: 0.3-0.9.
42.1	45.1	Diamicton: silt loam, sandy, and some pebbles	Chert: equant to blade, Carbonates; equant to blade, Sandstones and disc to equant.	Granules to large pebbles. Granules <4mm, S: L=8mm, I=4mm, S=3mm, M: L=11,I=10,S=6, L: L=30m, I=25mm, S=15mm.	Clasts: Roundness: 0.3-07 subangular (chert and carbonates) to subrounded (shield and sandstone). Sphericity: 0.3-0.9.
45.1	46.9	Sand & Gravel: silty	N/A (no recovery)	N/A	N/A
46.9	49.4	Diamicton: silt loam, sandy, and some pebbles	Chert: equant to blade, Carbonates; equant to blade, Sandstones and	Granules to large pebbles. Granules <4mm, S: L=8mm, I=4mm, S=3mm, M: L=11,I=10,S=6, L:	Clasts: Roundness: 0.3-07 subangular (chert and carbonates) to subrounded

			disc to equant.	L=30m, I=25mm, S=15mm.	(shield and sandstone). Sphericity: 0.3-0.9.
49.4	54.7	Sand, silt, & gravel: interbedded; very fine sand with silt from 49-52 m; medium to coarse sand with gravel with beds of very fine to fine sand from 52-53 m; very fine and fine sand and silt from 53-54 m	Chert: equant to blade, Carbonates; equant to blade, Sandstones and disc to equant.	Small to medium pebbles. S: L=8mm, I=4mm, S=3mm, M: L=11,I=10,S=6	Clasts: Roundness: 0.3-07 subangular (chert and carbonates) to subrounded (shield and sandstone). Sphericity: 0.3-0.9.

Top (m)	Bottom (m)	Texture	Sorting	Lithologies/Percentages	Matrix/Clast Percentages
25.0	31.1	Pitted carbonates, chipped smooth polished chert. Smooth sandstones.	Poor	Clasts: Dolostone, chert, sandstone, siltstone	Matrix supported silt diamicton. Approx. 15% pebbles.
31.1	32.6	Pitted carbonates, chipped smooth polished chert. Smooth sandstones and shield clasts.	Poor	Clasts: Dolostone, chert, sandstone, siltstone. Shield lithologies. Grains: Q=55 (subrounded), F=10 (rounded), RF=35 (subangular to sub-rounded).	Matrix supported sand and gravel. Approx. 49% pebbles.
32.6	34.1	Pitted carbonates, chipped smooth polished chert. Smooth sandstones.	Poor	Clasts: Dolostone, chert, sandstone, siltstone	Matrix supported silt loam diamicton. Approx. 20% pebbles.
34.1	35.4	Smooth rounded granules	Well	Clasts: Dolostone, chert, sandstone, siltstone. Grains: Q=65, F=10, RF=25.	Matrix supported sand with gravel in beds.
35.4	42.1	Pitted carbonates, chipped smooth polished chert. Smooth sandstones.	Moderate to poor	Clasts: Dolostone, chert, sandstone, siltstone. Grains: Q=60, F=15, RF=25.	Matrix supported sand approx. 5% pebbles.
42.1	45.1	Pitted carbonates, chipped smooth polished chert. Smooth sandstones.	Moderate	Clasts: Dolostone, chert, sandstone, siltstone.	Matrix supported silt loam diamicton approx. 20% pebbles.
45.1	46.9	N/A	N/A	N/A	N/A
46.9	49.4	Pitted carbonates, chipped smooth polished chert. Smooth sandstones.	Moderate	Clasts: Dolostone, chert, sandstone, siltstone.	Matrix supported silt loam diamicton approx. 5% pebbles.

49.4	54.7	Pitted carbonates, chipped smooth polished chert. Smooth sandstones.	Well to moderate	Clasts: Dolostone, chert, sandstone, siltstone.	Matrix-supported sand.

Top (m)	Bottom (m)	Colour	Munsell	Sedimentary Structures	Lithofacies Code	Additional Comments	Model Code
25.0	31.1	Brown to light yellowish brown (oxidized looking) as first 1 m is leached	10YR 4/3 to 6/4	N/A	Dmm	Photograph: 101-0235 & Photograph: 101-0236	C
31.1	32.6	Grayish brown (oxidized)	2.5Y 5/2	N/A	Sm/Gms	Photograph: 101-0236	C
32.6	34.1	Dark grayish brown	10YR 4/2	N/A	Dmm	Photograph: 101-0237 (sharp contact)	C
34.1	35.4	Grayish brown	2.5Y 5/2	Horizontal laminations/ bedding	Sm/Sh, Sm/Gms	Photograph: 101-0237	B
35.4	42.1	Grayish brown	2.5Y 5/2	N/A	Sm	Photograph: 101-0237	B
42.1	45.1	Dark grayish brown	10YR 4/2	N/A	Dmm	Photograph: 101-0237 & Photograph: 101-0238	C
45.1	46.9	N/A	N/A	N/A	Dmm	N/A	C
49.4	54.7	Brown to grayish brown	10YR 5/3 to 10 YR 5/2	Interbedded	Sm/Gms	Photograph: 101-0238 & Photograph: 101-0239	B

Photograph: 101-0235
19.8-27.4 m (65-90 ft)

Photograph: 101-0237
31.1-43.6 m (112-143 ft)

Photograph: 101-0236
27.4-31.1 m (90-112 ft)

Photograph: 101-0238
43.6-49.5 m (143-162.5 ft)

Photograph: 101-0239
49.5-54.7 m (164-179.4 ft)

Figure A.7: Core photographs of CHAM-07-04A of the Glasford deglacial unit composed of repeated facies assemblage C and B.

Table A.8. Description of Higginsville Section

Top (m)	Bottom (m)	Material	Clast Morphology	Clast Measurements	Roundness
3.7	3.7	Sandy silt: fine to medium sand, granules, olive brown	Prolate to equant	Granules: L:6mm, I:4mm, S:3mm	Subangular to subrounded
3.7	3.8	Sandy silt.	N/A	N/A	N/A
3.8	3.9	Sandy silt: fine to medium sand, granules, olive brown	prolate to equant	Granules: L:6mm, I:4, S:3	Subangular to subrounded
3.9	4.0	Fine to medium sand: some gravel.	N/A	N/A	N/A
4.0	4.0	Sand: fine to coarse sand with gravel. Beds of fine sand.	N/A	Granule to medium.	N/A
4.0	4.1	Diamicton: silt-rich some gravel. Sand interbeds. Sharp contact with above sands.	N/A	Granule to large.	N/A
4.1	4.2	Diamicton: sandy, beds of sand. Graded contact with above silt loam diamicton.	N/A	Gravel: granule to medium	N/A
4.2	4.2	Diamicton: with beds of sand (fine to medium).	N/A	Gravel: granule to large	N/A
4.2	4.3	Diamicton: silt loam sandy. Gradual contact.	N/A	Gravel: granule to large	N/A
4.3	4.4	Diamicton: silt loam sandy. Gradual contact.	N/A	Granule to large.	N/A
4.4	4.4	Diamicton: silt loam sandy. Gradual contact.	N/A	Granule to large.	Angular to subrounded.
4.4	4.5	Diamicton: silt loam sandy. Gradual contact.	N/A	Granule to large.	Angular to subrounded.
4.5	4.6	Diamicton: silt loam sandy. Gradual contact.	N/A	Granule to large.	Angular to subrounded.
4.6	4.6	Diamicton: silt loam sandy. Gradual contact.	N/A	Granule to large.	Angular to subrounded.
4.6	4.7	Diamicton: silt loam sandy. Gradual contact.	N/A	Granule to large.	Angular to subrounded.
4.7	4.7	Sand: fine to coarse sand, trace gravel. Sharp contact with lower diamicton.	N/A	Granule to large.	N/A

4.7	4.8	Sand: some silt. Very fine to fine. Trace gravel. Sharp contacts.	N/A	Granules.	N/A

Top (m)	Bottom (m)	Texture	Sorting	Lithologies/Percentages	Matrix/Clast Percentages
3.7	3.7	Pitted and chipped	Moderate to well: small amounts of granules mostly fine-grained matrix	N/A	Matrix supported (sand): 10% granules
3.7	3.8	N/A	Well	N/A	Matrix supported: silt
3.8	3.9	Pitted and chipped	Moderate to well: small amounts of granules mostly fine-grained matrix	N/A	Matrix supported (sand): 10% granules
3.9	4.0	N/A	Moderate to well	N/A	N/A
4.0	4.0	N/A	Moderate to poor	Gravel: chert etc.	Matrix supported (sand).
4.0	4.1	N/A	Poor to moderate	Gravel: dolostone, limestone, chert, sandstone, etc.	Matrix supported (silt).
4.1	4.2	N/A	Well	10% gravel	Matrix supported
4.2	4.2	N/A	Moderate	20% gravel	Matrix supported
4.2	4.3	N/A	Moderate	N/A	Matrix supported
4.3	4.4	N/A	Moderate	Chert etc.	Matrix supported
4.4	4.4	Weathered, pitted, and cracked. Smooth (sandstone).	Moderate to poor	N/A	Matrix supported (sand and silt).
4.4	4.5	Weathered, pitted, and cracked. Smooth (sandstone).	Moderate to poor	N/A	Matrix supported (sand and silt).
4.5	4.6	Weathered, pitted, and cracked. Smooth (sandstone).	Moderate to poor	N/A	Matrix supported (sand and silt).
4.6	4.6	Weathered, pitted, and cracked. Smooth (sandstone).	Moderate to poor	N/A	Matrix supported (sand and silt).
4.6	4.7	Weathered, pitted, and cracked. Smooth (sandstone).	Moderate to poor	N/A	Matrix supported (sand and silt).
4.7	4.7	N/A	Moderate	Chert etc.	Matrix supported (sand).
4.7	4.8	N/A	Well	N/A	Matrix supported (sand).

Top (m)	Bottom (m)	Colour	Munsell	Sedimentary Structures	Lithofacies Code	Additional Comments	Model Code
3.7	3.7	Olive brown (oxidized)	2.5Y 4/3	N/A	Sm, Fm, Gms	Photographs taken Aug'10	B
3.7	3.8	Brown to yellow-brown (oxidized)	10YR 5/3 to 10YR 5/4	Horizontal laminations	Fl	Photographs taken Aug'10	B
3.8	3.9	Olive brown (oxidized)	2.5Y 4/3	N/A	Sm, Fm, Gms	Photographs taken Aug'10	B
3.9	4.0	Yellow-brown to gray brown	10YR 5/4 to 10YR 5/2	Horizontal laminations	Sh, Sm, Gms	Photographs taken Aug'10	B
4.0	4.0	Gray-brown to brown	10YR 5/2 to 10YR 5/3	Cross-bedding	Sh, Sm, Gms	Photographs taken Aug'10	B
4.0	4.1	Gray to gray-brown	10YR 5/1 to 2.5Y 5/2	Massive	Dmm	Photographs taken Aug'10	C
4.1	4.2	Brown to gray-brown	10YR 5/3 to 10YR 5/2	Massive	Dmm, Sm	Photographs taken Aug'10	C
4.2	4.2	Yellow-brown to brown-gray	10YR 5/4 to 10YR 5/2	Massive	Dmm, Sm	Photographs taken Aug'10	C
4.2	4.3	Brown to gray-brown	10YR 5/3 to 10YR 5/2	Massive	Dmm, Sm	Photographs taken Aug'10	C
4.3	4.4	Brown to gray-brown	10YR 5/3 to 10YR 5/2	Massive	Dmm, Sm	Photographs taken Aug'10	C
4.4	4.4	Brown to gray-brown	10YR 5/3 to 10YR 5/2	Massive	Dmm, Sm	Photographs taken Aug'10	C
4.4	4.5	Brown to gray-brown	10YR 5/3 to 10YR 5/2	Massive	Dmm, Sm	Photographs taken Aug'10	C
4.5	4.6	Brown to gray-brown	10YR 5/3 to 10YR 5/2	Massive	Dmm, Sm	Photographs taken Aug'10	C
4.6	4.6	Brown to gray-brown	10YR 5/3 to 10YR 5/2	Massive	Dmm, Sm	Photographs taken Aug'10	C
4.6	4.7	Brown to gray-brown	10YR 5/3 to 10YR 5/2	Massive	Dmm, Sm	Photographs taken Aug'10	C
4.7	4.7	Yellow brown to brown.	10YR 5/4 to 10YR 5/2	Lamination	Sm, Sh	Photographs taken Aug'10	B
4.7	4.8	Yellow brown to brown.	10YR 5/4 to 10YR 5/2	N/A	Sm	Photographs taken Aug'10	B

Figure A.8: Higginsville section exposed along the Middle Fork River in Vermillion County, east-central Illinois.

Figure A.9: Trench at the Higginsville section where sediments assigned to the Glasford deglacial unit were described.

APPENDIX B

Digital Appendices

The files stored on the accompanying DVD include digital databases, gOcad surfaces, SGRIDs, detailed core descriptions and photographs, grain size data and associated statistics, photographs of core and outcrop, and calculations of hydraulic conductivity. The data files from gOcad are saved as object files either: .ts for surfaces and .sg for SGRIDs. These files can be imported into a number of 3-D geomodelling software and 3-D viewers including gOcad, GSI3D (the British Geological Survey's geomodelling software), etc. Surfaces for the creation of the Glasford model have been included in the attached DVD. Other core and outcrop data including and hydraulic properties and grain size analyzes are on the DVD in .xlxs format. Digital databases of the Glasford model and all other data sources have also been included as a part of the geomodelling process. The following is a schematic outline of the contents of each folder of data on the DVD.

Folder 1:

Core descriptions and grain size (.xlxs)		
Cross-section 1 data	**Cross-section 2 data**	**Cross-section 3 data**
CHAM-08-05	CHAM-09-07	CHAM-07-01A
CHAM-08-07A	FORD-08-01A	CHAM-07-04A
Foosland Well		

* Each continuous core description includes grain size analyzes, photographs, downhole geophysical logs, and other available resources.

Folder 2:

Geomodelling Data (.xlxs)	
Glasford database	
Glasford modeling data and model codes	All data for ISGS and Glasford models

Folder 3:

gOcad Files for Glasford model
SGRID- Glasford model.sg
Surfaces- GlasfordModel_surfaces.ts

Folder 4:

Hydraulic Properties and grain size statistics (.xlxs)
Hydraulic Conductivity calculations

Folder 5:

Outcrop and grain size (.xlxs)
Higginsville Section

* Outcrop description includes grain size analyzes and Photographs.

APPENDIX C

High-Quality Borehole Data

Descriptions of continuous data used for the Glasford model were generalized to set standardized terms (Table 3.1). This methodology is outlined in Chapter 3. All continuous core data was collected as a part of the Mahomet aquifer study in east-central Illinois (cf. Stumpf and Dey in press).

Table C.1. High-quality well data used for the construction of the Glasford model.

Borehole	Top (m)	Bottom (m)	Material	Material Comment	Standard Code
Foosland	33.8	35.7	Diamicton	Diamicton; sandy loam, lots of gravel, some silt vry- fine to medium sand	D
Foosland	35.7	36.6	Diamicton	Diamicton; silty with beds of sand, some cobbles, vry fine to fine sand	D
Foosland	36.6	41.1	Sand and Gravel	Sand and gravel; fine to medium sand, Fine sand @ 134.8-140 feet Gravel @120-122 feet	S2(3)-G1(2)/D
Foosland	41.1	43.3	Clay	Clay; some silt, no clasts	F1
Foosland	43.3	45.7	Sand and Gravel	Sand; silty, vry fine to fine sand, trace gravel @ 142-143 feet	S2(3)-G1(2)/D
Foosland	45.7	46.3	Sand	Sand; fine to medium. No gravel	S2
Foosland	46.3	46.6	Sand	Sand; silty-vry-fine sand	S1
Foosland	46.6	48.8	Sand	Sand; fine to med. Sand with no gravel	S2
Foosland	48.8	49.8	Sand	Sand; vry fine to fine . Sand no gravel	S1
Foosland	49.8	50.6	Sand	Sand; vry fine to medium, with no gravel	S2
Foosland	50.6	52.1	Sand	Sand; med. To coarse sand, no gravel	S3
Foosland	52.1	52.4	Sand	Sand; vry fine- med sand; no gravel	S1
Foosland	52.4	53.0	Sand	Sand; vry fine to medium, with no gravel	S1
Foosland	53.0	53.9	Clay	Clay; some silt, no clasts	F1
Foosland	53.9	54.3	Sand	Sand; vry fine to fine . Sand no gravel	S1
CHAM-03-01	15.2	18.3	sand	fine to coarse sand with some gravel	OS2(3)-G1(2)/D
CHAM-03-01	18.3	18.9	sand	fine to coarse sand with some gravel	S2(3)-G1(2)/D
CHAM-03-01	18.9	19.5	silt and sand	sand is vry fine at top and coarsens to medium	F2
CHAM-03-01	19.5	20.1	poor recovery: sand		S
CHAM-03-01	20.1	23.5	diamicton	slightly coarser from 71-75 feet	D

CHAM-03-01	23.5	25.6	diamicton		D
CHAM-03-01	25.6	28.3	diamicton		D
CHAM-03-01	28.3	30.8	poor recovery; diamicton		D
CHAM-03-01	30.8	33.8	poor recovery; diamicton		D
CHAM-03-01	33.8	36.3	partial recovery; gravel and sand	sand vry fine to fine with silt; no recovry from 115-117 feet	S2(3)-G1(2)/D
CHAM-03-01	36.3	37.8	sand with beds of silt and clay	fine to vry fine sand	S1-F1
CHAM-03-01	37.8	38.7	sand with beds of silt	fine to coarse sand; coarsens downwards	S1-F1
CHAM-03-02	23.8	28.7	diamicton	sandy; some pebbles	D
CHAM-03-02	28.7	32.3	sand and gravel		S2(3)-G1(2)/D
CHAM-03-02	32.3	42.1	diamicton	pebbly; contains beds of sand and gravel	D
CHAM-03-02	42.1	57.0	diamicton	sandy and pebbly	D
CHAM-03-03	27.7	34.7	diamicton	gravelly and pebbly;	D
CHAM-03-03	34.7	36.6	silt and sand	vry fine to fine sand	S1
CHAM-03-03	36.6	41.1	sand and gravel	fine to coarse sand; silty; contains beds of fine to medium sand	S1-F1
CHAM-07-01A	26.2	27.7	diamicton		D
CHAM-07-01A	27.7	30.2	sand or diamicton		S
CHAM-07-01A	30.2	33.5	sand with silt	fine to medium sand	S1-F1
CHAM-07-01A	33.5	35.1	sand and silt	with beds of diamicton	S1-F1
CHAM-07-01A	35.1	36.6	diamicton	sandy	D
CHAM-07-01A	36.6	47.5	sand and gravel	interbedded; fine to coarse sand and gravel from 120-130 feet; well sorted fine to medium sand from 130-140 feet; fine to vry coarse sand with beds of gravel from 140-147 feet; fine sand from 147-156 feet	S2(3)-G1(2)/D
CHAM-07-01A	47.5	51.2	sand and gravel	pebbly; medium to vry coarse sand; more pebbles at bottom	S2(3)-G1(2)/D
CHAM-07-02A	24.7	30.5	diamicton	contains beds of sand and gravel	D
CHAM-07-02A	30.5	32.6	sand	vry fine to medium sand with few gravel; some beds of silt below 102 feet	S
CHAM-07-02A	32.6	35.5	sand	fine to coarse sand with silt and small gravel; contains some beds of silt and vry fine to fine sand below 111 feet	S1-F1
CHAM-07-02A	35.5	40.2	silt, sand, and silt and clay	fine sand; some beds of sand and gravel and diamicton; sand and gravel from 125-128 feet	F2
CHAM-07-02A	40.2	43.7	diamicton	pebbly sandy diamicton from 132-137 feet; silty diamicton from	D

				137-143.5 feet; some pebbles below 137 feet; some beds of silt and fine sand below 133 feet	
CHAM-07-03A	11.4	13.1	diamicton	sandy	D
CHAM-07-03A	13.1	23.2	diamicton	silty from 43-57 feet; sandy from 57-76 feet; pebbly below 64 feet	D
CHAM-07-03A	23.2	25.3	sand and gravel	pebbly; contains some beds of silt	S2(3)-G1(2)/D
CHAM-07-03A	25.3	30.8	diamicton	contains beds of sand and gravel; gravelly from 84-86 feet	D
CHAM-07-03A	30.8	32.6	sand, gravel, and diamicton	interbedded	S2(3)-G1(2)/D
CHAM-07-04A	25.1	31.1	diamicton	sandy and gravelly; some pebbles; vry fine to fine sand with gravel from 85-87.5 feet	D
CHAM-07-04A	31.1	32.6	sand and gravel	silty	S2(3)-G1(2)/D
CHAM-07-04A	32.6	34.1	diamicton	sandy	D
CHAM-07-04A	34.1	35.4	sand	vry fine to fine with silt	S1-F1
CHAM-07-04A	35.4	42.1	sand	fine to coarse sand; contains beds of pebbly sand and gravel	S3
CHAM-07-04A	42.1	45.1	diamicton	sandy; some pebbles	D
CHAM-07-04A	45.1	46.9	sand and gravel		S2(3)-G1(2)/D
CHAM-07-04A	46.9	49.4	diamicton		D
CHAM-07-04A	49.4	54.7	sand, silt, and gravel	interbedded; vry fine sand with silt from 162-172 feet; medium to coarse sand with gravel with beds of vry fine to fine sand from 172-175 feet; vry fine and fine sand and silt from 172-179.5 feet	S1-F1
CHAM-07-04B	26.2	32.0	Sand and Gravel	Sand and Gravel	S2(3)-G1(2)/D
CHAM-07-04B	32.0	34.1	Diamicton	Diamicton; sandy	D
CHAM-07-04B	34.1	35.4	Sand	Sand; silty	S1-F1
CHAM-07-04B	35.4	36.9	Sand and Gravel	Sand; pebbly, gravel	S2(3)-G1(2)/D
CHAM-07-04B	36.9	53.9	Sand	Fine to med. Sand	S2
CHAM-07-05	25.0	30.6	diamicton	gravelly and pebbly	D
CHAM-07-05	30.6	38.1	diamicton	silty	D
CHAM-07-05	38.1	42.4	diamicton	sandy	D
CHAM-07-06A	15.8	16.8	silt and sand	vry fine to fine sand	F2
CHAM-07-06A	16.8	18.0	sand and gravel	silty	S2(3)-G1(2)/D
CHAM-07-06A	18.0	20.7	diamicton	sandy; contains some beds of sand and gravel; some pebbles	D
CHAM-07-06A	20.7	27.0	sand and gravel	silty; fine to coarse sand; some beds of sandy diamicton	S2(3)-G1(2)/D
CHAM-07-07	18.3	28.2	diamicton	sandy	D
CHAM-07-07	28.2	32.5	sand and gravel		S2(3)-G1(2)/D
CHAM-07-07	32.5	33.5	diamicton		D
CHAM-07-08	35.1	42.4	diamicton	gravelly	D

CHAM-07-08	42.4	48.2	sand		S
CHAM-07-08	48.2	51.5	sand and gravel		S2(3)-G1(2)/D
CHAM-08-01	31.1	36.3	diamicton	pebbly	D
CHAM-08-01	36.3	38.1	silt and sand	vry fine to fine sand; contains some clasts of silt and clay	F1-S1
CHAM-08-02A	25.9	31.4	sand and silt	vry fine to fine sand; some beds of diamicton at bottom	S1-F1
CHAM-08-02A	31.4	37.0	diamicton	sandy; some pebbles	D
CHAM-08-02A	37.0	48.3	sand and gravel an silt and clay	fine to coarse sand; some beds of gravel and diamicton ; few pebbles	S2(3)-G1(2)/D
CHAM-08-02A	48.3	52.4	sand and gravel	medium to vry coarse sand; some pebbles; some thin beds of fine sand	S2(3)-G1(2)/D
CHAM-08-02A	52.4	54.7	sand	vry fine to medium sand	S2(3)-G1(2)/D
CHAM-08-03A	33.5	38.1	diamicton	sandy; some pebbles; upper 2 feet part of B-horizon soil	OD
CHAM-08-03A	38.1	46.9	sand and gravel		S2(3)-G1(2)/D
CHAM-08-03A	46.9	52.7	diamicton		D
CHAM-08-04	22.6	24.1	silt and clay		F1
CHAM-08-04	24.1	24.9	sand and silt		S1-F1
CHAM-08-04	24.9	27.4	diamicton	pebbly; becomes siltier with depth; contains rip-up clasts of silt and clay at bottom	D
CHAM-08-04	27.4	28.8	silt, sand, clay	sand is fine to vry fine; some rip-up clasts of silt and clay	F2
CHAM-08-04	28.8	32.0	silt and sand	interbedded silt and fine to vry fine sand	F2
CHAM-08-04	32.0	32.9	gravel and silt		D
CHAM-08-04	32.9	34.7	silt and diamicton	interstratified; upper 4 feet more silt; diamicton is pebbly	D
CHAM-08-05	30.2	33.2	diamicton	pebbly; contains beds of sand and gravel	D
CHAM-08-05	33.2	38.7	diamicton	silty; many pebbles and gravel; some cobbles; some gravel zones throughout; vry pebbly at bottom	D
CHAM-08-06	39.2	45.4	diamicton	sandy; with beds of silt and sand; some pebbles	D
CHAM-08-06	45.4	47.9	diamicton	fine to medium sand with gravel from 154-157 feet	D
CHAM-08-06	47.9	49.7	silt and sand	vry fine to fine sand from 157-162 feet; fine to coarse sand and gravel from 162-163 feet	F1-S1
CHAM-08-07A	20.0	22.3	diamicton	cobbly	D
CHAM-08-07A	22.3	24.1	diamicton	vry sandy; contains beds of sand and gravel	D
CHAM-08-08A	18.0	22.4	diamicton	gravelly; some pebbles	D
CHAM-08-08A	22.4	29.0	diamicton	silty; with beds of silt; some pebbles	D
CHAM-08-08A	29.0	31.7	sand and gravel	silty; with beds of fine sand and silt	S2(3)-G1(2)/D
CHAM-08-08A	31.7	37.8	diamicton	sandy; contains beds of silt and fine sand	D
CHAM-08-09A	17.2	17.7	sand and silt	vry fine to fine sand	S1-F1

CHAM-08-09A	17.7	20.7	sand and gravel	fine to vry coarse sand; some pebbles; fine to medium sand with some gravel from 58-61 feet	S2(3)-G1(2)/D
CHAM-08-09A	20.7	21.9	sand and gravel	vry pebbly; silty	S2(3)-G1(2)/D
CHAM-08-09A	21.9	23.2	sand with gravel	medium to vry coarse sand; some beds of gravel; some pebbles; some inclusions of red coloured sand	S2(3)-G1(2)/D
CHAM-08-10A	31.3	32.3	diamicton	contains bed of sand and gravel	OD
CHAM-08-10A	32.3	35.7	sand		S
CHAM-08-10A	35.7	39.5	diamicton	sandy; some pebbles; a few beds of sand and silt	D
CHAM-09-01	30.2	31.5	diamicton	pebbly; contain some beds or inclusions of f-m sand	OD
CHAM-09-01	31.5	32.0	sand, silt, and diamicton	interbedded; fine to vry fine sand	OS1-F1
CHAM-09-01	32.0	38.1	diamicton	sandy; some pebbles; some beds of sand and silt	D
CHAM-09-01	38.1	42.7	diamicton	sandy to gravelly; bed of f-m sand from 135-136 feet	D
CHAM-09-01	42.7	45.3	sand	vry fine to fine with silt; contains some beds of f-m sand; silt from 147-148.5 feet	S1-F1
CHAM-09-01	45.3	47.2	silt	silt and clay 148.5-149.5 feet and 152.5-153 feet	F1
CHAM-09-01	47.2	54.9	sand	vry fine to medium	S2
CHAM-09-02A	35.5	35.9	silt and sand	vry fine to fine sand	F2
CHAM-09-02A	35.9	36.2	diamicton	some interbeds of fine to medium sand and some gravel	D
CHAM-09-02A	36.2	37.3	diamicton	fine to medium sand	D
CHAM-09-02A	37.3	38.4	diamicton	gravelly	D
CHAM-09-02A	38.4	39.0	diamicton	some gravel and pebbles	D
CHAM-09-02A	39.0	39.5	sand	fine to medium sand and some silt	S1-F1
CHAM-09-02A	39.5	39.6	diamicton	some interbeds of sand	D
CHAM-09-02A	39.7	40.2	sand	fine to medium sand and some gravel and silt	S2(3)-G1(2)/D
CHAM-09-02A	40.2	40.7	silt and clay	few pebbles	F1
CHAM-09-02A	40.7	41.0	silt and fine sand		F2
CHAM-09-02A	41.0	41.1	silt and clay	few pebbles	D
CHAM-09-02A	41.1	42.1	sand with silt	fine sand	S1-F1
CHAM-09-02A	42.1	42.4	silt and clay	few pebbles	D
CHAM-09-02A	42.4	42.6	sand	fine to medium	S2
CHAM-09-02A	42.6	42.7	silt with sand	vry fine sand	F2
CHAM-09-02A	42.7	43.6	sand and silt	vry fine to coarse; laminated silt and clay between 139.7 and 140 feet	S1-F1
CHAM-09-02A	43.6	45.1	sand and silt	vry fine, but coarsens with depth to fine to medium	S1-F1
CHAM-09-02A	45.1	46.3	sand	fine to medium; coarser material in bottom 2 feet [no recovry]	S2

CHAM-09-02A	46.3	49.7	sand [partial recovery]	medium to coarse	S2
CHAM-09-02A	49.7	50.0	sand and gravel	medium to coarse sand with gravel at the bottom; some pebbles	S2(3)-G1(2)/D
CHAM-09-02A	50.0	50.1	silt	silt with beds of diamicton; some gravel and pebbles	D
CHAM-09-03A	17.7	18.0	sand	medium to coarse with bed of silt at base	S1-F1
CHAM-09-03A	18.0	19.5	sand and gravel	fine to coarse sand with small gravel; some pebbles at base	S2(3)-G1(2)/D
CHAM-09-03A	19.5	21.0	diamicton?	sandy	D
CHAM-09-03A	21.0	23.2	diamicton	bed of sand and silt from 75-76 feet	D
CHAM-09-04A	20.6	22.3	sand	vry fine to medium sand; few gravel and pebbles	OS2
CHAM-09-04A	22.3	23.6	sand, gravel, silt	interbedded fine to vry coarse sand and gravel with silt and fine sand beds	OS2(3)-G1(2)/D
CHAM-09-04A	23.6	29.3	sand and gravel	interbeds of silt and fine sand	S2(3)-G1(2)/D
CHAM-09-04A	29.3	32.9	sand and gravel	pebbly	S2(3)-G1(2)/D
CHAM-09-04A	32.9	38.1	diamicton	sandy; pebbly and gravelly	D
CHAM-09-04A	38.1	40.8	sand and gravel	silty; fine to coarse sand; some beds of diamicton; some pebbles	S2(3)-G1(2)/D
CHAM-09-04A	40.8	50.3	sand and gravel	medium to coarse sand; pebbly at bottom	S2(3)-G1(2)/D
CHAM-09-05A	14.0	14.9	silt and sand	vry fine to fine sand; few gravel	OF2
CHAM-09-05A	14.9	15.6	sand and gravel	medium to coarse sand; some pebbles	S2(3)-G1(2)/D
CHAM-09-05A	15.6	17.7	sand with silt	vry fine to coarse sand; some interbeds of sand and gravel	S1-F1
CHAM-09-05A	17.7	24.4	sand	vry fine to fine sand	S2
CHAM-09-05A	24.4	29.0	sand	vry fine to medium sand; some beds of coarse to vry coarse sand	S2
CHAM-09-05A	29.0	33.0	sand and gravel	medium to vry coarse sand; pebbly	S2(3)-G1(2)/D
CHAM-09-06	19.8	20.7	silt		F1
CHAM-09-06	20.7	22.9	silt	some intervals of bedded of silt and clay	F1
CHAM-09-06	22.9	23.3	silt and clay	small thin beds of fine sand	F1
CHAM-09-06	23.3	24.9	sand and some silt		S1-F1
CHAM-09-06	24.9	26.2	silt, sand, clay	interbedded	F2
CHAM-09-06	26.2	28.7	silt	some clay	F1
CHAM-09-06	28.7	29.3	sand	gravelly	S2(3)-G1(2)/D
CHAM-09-06	29.3	29.6	silt with sand		F2
CHAM-09-06	29.6	30.5	silt and clay		F1
CHAM-09-06	30.5	30.9	silt and some sand		F2
CHAM-09-06	30.9	31.2	sand; gravel and small cobbles	medium to coarse sand; some interbeds of gravel	S2(3)-G1(2)/D
CHAM-09-06	31.2	32.2	sand	fine sand with beds of coarse sand and gravel	S2(3)-G1(2)/D

CHAM-09-06	32.2	33.1	sand	fine sand and silt with some gravel	S2(3)-G1(2)/D
CHAM-09-06	33.1	33.2	sand and gravel	sand is medium to coarse	S2(3)-G1(2)/D
CHAM-09-06	33.2	34.4	diamicton	some beds of fine sand, gravel and small cobbles	D
CHAM-09-06	34.4	37.2	sand	fine to medium	S2
CHAM-09-06	37.2	38.4	silt with sand	fine sand; bed of sand from 125-126 ft	F2
CHAM-09-07	10.7	11.6	Sand with gravel	sand is medium to coarse; some eluvial clay throughout	OS2(3)-G1(2)/D
CHAM-09-07	11.6	14.5	Silt and sand with gravel	some pebbles	OF2
CHAM-09-07	14.5	17.2	Sand with gravel	medium to coarse sand with some silt; beds of pebbly gravel at 49.5 and 56.0 feet	OS2(3)-G1(2)/D
CHAM-09-07	17.2	17.5	Sand	fine sand	S1
CHAM-09-07	17.5	18.7	Sand and gravel	medium to coarse sand with some silt; some pebbles	S2(3)-G1(2)/D
CHAM-09-07	18.7	22.9	Gravel	pebbly; cemented	G
CHAM-09-07	22.9	25.7	Sand with gravel	medium to coarse sand; some beds of gravelly sand	S2(3)-G1(2)/D
CHAM-09-07	25.7	27.4	Gravel	pebbly; cemented; fewer pebbles than 61.5 to 75.0 feet	G
CHAM-09-07	27.4	30.5	Sand	fine to medium sand with some coarse sand and gravel; possible gravel beds between 97.0 and 100.0 feet	S2(3)-G1(2)/D
CHAM-09-07	30.5	33.8	Sand	medium to coarse sand with some gravel; minor silt and fine sand	S2(3)-G1(2)/D
CHAM-09-07	33.8	38.1	Sand	fine to medium sand; slightly finer grained in upper part	S2
CHAM-09-07	38.1	41.1	Sand	medium to fine; some thin beds of heavy minerals; lower part weakly cemented	S2
CHAM-09-07	41.1	42.7	Sand	medium with some fine sand; scattered pebbles; a few thin beds of silty diamicton	S2
CHAM-09-07	42.7	44.2	Sand and gravel	some pebbles; some silt in lower part where it becomes finer grained	S2(3)-G1(2)/D
CHAM-09-07	44.2	44.8	Sand with gravel	medium to coarse sand; some silt	S2(3)-G1(2)/D
CHAM-09-08	26.2	29.3	diamicton or sand and gravel	some elluvial clay?	OD
CHAM-09-08	29.3	30.8	sand with gravel	sand is vry fine to medium	S2(3)-G1(2)/D
CHAM-09-08	30.8	38.7	diamicton	few beds of sand and gravel	D
CHAM-09-08	38.7	45.4	diamicton with interbeds of sand	sand is vry fine to fine	D
CHAM-09-08	45.4	48.2	sand	vry fine to medium with some few coarse sand and gravel	S
FORD-08-01A	16.8	20.4	sand and gravel	silty	S2
FORD-08-01A	20.4	24.7	diamicton	sandy; some beds of sand and gravel	D
FORD-08-01A	24.7	35.1	sand	fine to medium sand; contains beds of gravel; some pebbles	S2

FORD-08-01A	35.1	36.3	sand and gravel	fine to coarse sand	S2(3)-G1(2)/D
MCLN-08-01	22.6	26.2	diamicton	gravelly; some pebbles and cobbless	D
MCLN-08-01	26.2	32.6	diamicton	sandy and pebbly; contains some beds of sand and silt; sand and gravel from 90-94.5 feet; sandy diamicton from 105-107 feet	D
MCLN-08-01	32.6	36.6	silt, sand, and diamicton	interbedded; silt sand vry fine to fine sand from 107-110 feet; vry stiff sandy diamicton with some beds of sand and silt from 110-115 feet; vry fine to fine sand and silt with beds of diamicton from 115-120 feet	F2
PIAT-07-01	27.1	29.0	sand and gravel		S2(3)-G1(2)/D
PIAT-07-01	29.0	32.3	diamicton	sandy and gravelly	D
PIAT-07-01	32.3	38.1	sand and silt	vry fine to fine sand; some beds of sand and gravel	S1-F1
PIAT-07-01	38.1	42.1	sand and gravel	fine to coarse sand	S2(3)-G1(2)/D
PIAT-07-02A	10.4	13.0	sand	fine to medium; contains a few pebbles	OS2
PIAT-07-02A	13.0	15.4	diamicton		OD
PIAT-07-02A	15.4	18.3	sand and gravel	some silt; fine to vry coarse sand; some pebbles; vry fine to fine sand and silt from 50.5-51.5 feet	S2(3)-G1(2)/D
PIAT-07-02A	18.3	28.0	diamicton	sandy to silty; some beds of sand and gravel and silt	D
PIAT-07-02A	28.0	29.3	sand and silt	vry fine to fine sand; sand and gravel from 94-96 feet	S1-F1
PIAT-07-02A	29.3	37.5	diamicton	gravelly and pebbly; some thin beds of silt and sand	D
PIAT-08-01	7.9	17.7	diamicton	sandy and gravelly; some beds of silt and clay from 47-48 feet and 51-52 feet; sand and gravel from 45-47 feet	D
PIAT-08-01	17.7	21.9	diamicton	silty; contains interbeds of silt and vry fine sand	D
PIAT-08-01	21.9	25.0	sand and gravel and diamicton	interbedded; pebbly to gravelly diamicton; pebbly sand and gravel	S2(3)-G1(2)/D
PIAT-08-02	7.3	12.2	diamicton	sandy; contains some beds of sand and gravel and pebbles	D
PIAT-08-02	12.2	14.3	diamicton	silty; some gravel; contains a few inclusions of reddish brown diamicton	D
PIAT-08-02	14.3	18.9	sand with gravel	mostly fine to coarse sand; vry fine to medium sand with silt from 50-53 feet; diamicton? from 53-55 feet	S2(3)-G1(2)/D
PIAT-08-02	18.9	21.0	silt and sand		F2
PIAT-08-02	21.0	23.6	sand with gravel	fine to medium sand; few pebbles	S2(3)-G1(2)/D
PIAT-08-02	23.6	26.7	diamicton	sandy and pebbly; contains some beds of vry fine to fine sand and silt; sandier from 85-87.5 feet; gravel at bottom; some inclusions of reddish brown diamicton in the upper part	D
PIAT-09-01A	9.9	11.7	diamicton	sandy	D
PIAT-09-01A	11.7	13.3	diamicton and silt	silty to sandy diamicton	D

PIAT-09-01A	13.3	20.4	sand with gravel	fine to coarse sand; some pebbles	S2(3)-G1(2)/D
PIAT-09-01A	20.4	24.5	silt and sand	vry fine to fine sand	F2
PIAT-09-01A	24.5	26.5	sand with gravel	fine to coarse sand; few pebbles	S2(3)-G1(2)/D
PIAT-09-01A	26.5	29.6	sand with silt	fine to medium sand	S1-F1
PIAT-09-01A	29.6	31.2	sand	medium to coarse sand	S2
PIAT-09-01A	31.2	42.1	sand and gravel	medium to fine sand; pebbly	S2(3)-G1(2)/D
VERM-08-01A	9.9	18.6	sand	few gravel and pebbles	S
VERM-08-01A	18.6	22.7	sand and silt	vry fine to fine; sand and gravel from 66.5-70.5 feet	S1-F1

APPENDIX D

Grain Size Statistics

The grain size statistics for samples were taken from seven continuous cores. Descriptions of cores and the Higginsville section are provided in Chapter 2. Grain size statistics were used for the calculation of K-values in Appendix E and presented in Chapter 3, Table 3.8. Full grain size distributions are in the digital appendices on the DVD.

Table D.1. Grain size statistics for examined cores in Chapter 2.

Sample Identity	d_{10} (mm)	d_{50} (mm) (Median)	d_{60} (mm)	Methods of Moments (φ) Mean	Std. Dev.	Skewness	Kurtosis	I_o (mm)	Coefficient of Uniformity (U)	Porosity (n)
Borehole CHAM-08-05										
30.2-38.7 m (99-127 ft)	0.002	0.016	0.043	4.35	4.18	-0.51	1.97	0.0012	21.50	0.26
Borehole CHAM-08-07A										
20.0-24.1 m (65-79 ft)	0.004	0.15	0.2	3.17	3.54	0.17	2.46	0.002	50.00	0.26
Borehole FOOSLAND										
33.8-35.7 m (111-117 ft)	0.2	3	5	-0.55	2.66	1.72	6.32	0.1	25.00	0.26
35.6-36.6 m (117-120 ft)	0.004	0.32	0.4	2.96	3.41	0.43	2.4	0.0015	100.00	0.26
36.6-41.2 m (120-135 ft)	0.015	1.7	3.5	0.19	3.38	1.1	3.45	0.005	233.33	0.26
41.1-43.3 m (135-142 ft)	0.0016	0.0081	0.011	7.22	2.58	0.11	0.41	0.001	6.88	0.33
43.3-45.7 m (142-150 ft)	0.0095	0.2	0.22	3.34	2.03	1.77	5.88	0.005	23.16	0.26
45.7-46.3 m (150-152 ft)	0.16	0.23	0.26	2.38	1.14	4.54	28.8	0.14	1.63	0.44
46.3-46.6 m (152-153 ft)	0.0021	0.017	0.039	6.07	3.46	0.16	0.36	0.0012	18.57	0.26
46.6-48.8 m (153-160 ft)	0.05	0.18	0.19	3.1	1.96	1.46	5.12	0.038	3.80	0.38
48.8-50.6 m (160-166 ft)	0.038	0.12	0.15	3.51	1.92	1.38	4.98	0.03	3.95	0.38
50.6-52.1 m (166-171 ft)	0.13	0.26	0.285	2.37	1.59	2.88	13.32	0.1	2.19	0.43
52.1-52.4 m (171-172 ft)	0.09	0.198	0.2	2.87	1.6	2.77	11.97	0.075	2.22	0.42
52.4-53.0 m (172-174 ft)	0.09	0.36	0.395	2.08	2.22	1.43	4.55	0.07	4.39	0.37
53.0-53.9 m (174-177 ft)	0.0015	0.0075	0.0095	7.27	2.66	0.07	0.4	0.001	6.33	0.34
53.9-54.3 m (177-178 ft)	0.01	0.06	0.07	4.55	2.7	0.4	1.11	0.0065	7.00	0.33

Borehole FORD-08-01A										
16.8-20.4 m (55-67 ft)	0.07	0.8	1.2	0.2	2.2	1.59	6.64	0.05	17.14	0.27
20.4-24.7 m (67-81 ft)	0.0022	0.018	0.04	4.35	4.18	-0.51	1.97	0.0012	18.18	0.26
24.7-27.6m (81-90.5 ft)	0.13	0.42	0.5	1.54	1.62	3	14.7	0.095	3.85	0.38
27.6-28.2 m (90.5-92.5 ft)	0.038	0.28	0.32	2.51	2.06	1.72	6.48	0.02	8.42	0.31
28.2-29.6 m (92.5-97.0 ft)	0.12	0.46	0.51	1.34	2.01	1.73	8.31	0.07	4.25	0.37
29.6-32.6 m (97.0-107.0 ft)	0.12	0.39	0.45	1.74	1.76	2.49	10.69	0.08	3.75	0.38
32.6-35.1 m (107.0-115.0 ft)	0.03	0.41	0.5	1.9	2.26	1.47	5.87	0.018	16.67	0.27
35.1-36.3 m (115-119 ft)	0.5	1.3	1.8	-0.13	1.54	2.15	14.97	0.4	3.60	0.39
Borehole CHAM-09-07										
10.7-11.6 m (35-38 ft)	0.006	0.8	1.2	2.07	3.77	0.52	2.09	0.002	200	0.26
11.6-13.9 m (38-45.5 ft)	0.003	0.016	0.043	4.81	3.23	-0.24	2.33	0.0002	14.3	0.27
13.9-14.2 m (45.5-46.5 ft)	0.0073	0.4	0.48	2.40	2.75	1.30	4.13	0.0026	65.80	0.26
14.2-14.5 m (46.5-47.5 ft)	0.003	0.03	0.055	4.39	3.41	-0.09	2.02	0.002	18.30	0.26
14.5-16.9 m (47.5-55.5 ft)	0.3	1	1.3	0.75	1.64	3.97	18.56	0.2	4.3	0.37
16.9-17.5 m (55.5-57.5 ft)	0.4	1	1.3	0.51	1.48	3.8	21.96	0.3	3.25	0.40
17.5-18.8 m (57.5-61.5 ft)	0.2	1.2	1.6	0.24	2.02	2.38	10.07	0.15	8.00	0.31
22.9-25.7 m (75-84.2 ft)	0.4	0.9	0.95	0.57	1.51	4.45	22.59	0.32	2.38	0.42
27.4-30.5 m (90-100 ft)	0.05	0.18	0.19	3.1	1.96	1.46	5.12	0.04	3.80	0.38
30.5-33.5 m (100-110 ft)	0.16	0.5	0.6	1.34	1.66	2.98	14.05	0.12	3.75	0.38
33.5-36.6 m (110-120 ft)	0.078	0.23	0.24	2.61	1.85	1.83	6.88	0.065	3.08	0.40
36.6-42.7 m (120-140 ft)	0.09	0.2	0.35	2.08	2.12	1.39	4.67	0.07	3.89	0.38
42.7-44.8 m (140-147 ft)	0.27	4.2	6	-0.81	2.48	1.8	6.6	0.14	22.22	0.26
Borehole CHAM-07-01A										
30.2-33.5 m (99-110 ft)	0.02	0.2	0.25	3	3.23	0.41	0.87	0.015	12.50	0.28
33.5-35.1 m (110-115 ft)	0.003	0.015	0.04	5.87	3.27	0.13	0.47	0.002	13.33	0.28
35.1-36.6 m (115-120 ft)	0.0018	0.012	0.03	5.18	3.22	-0.23	2.7	0.001	16.67	0.27
36.6-39.6 m (120-130 ft)	0.03	0.25	0.3	2.78	2.95	0.58	1.34	0.019	10.00	0.30
39.6-42.7 m (130-140 ft)	0.04	0.4	0.5	2.14	3.17	0.56	1.2	0.025	12.50	0.28
42.7-44.8 m (140-147 ft)	0.17	0.35	0.4	1.76	1.57	33.19	16.31	0.12	2.35	0.42
44.8-47.6 m (147-156 ft)	0.14	0.2	0.21	2.71	1.32	4.06	22.06	0.11	1.50	0.45
47.6-51.2 m (156-168 ft)	0.5	0.8	1	0.1	1.04	5.95	46.71	0.4	2.00	0.43
Borehole CHAM-07-04A										
25.0-31.1 m (82-102 ft)	0.002	0.045	0.12	3.98	3.78	-0.12	1.9	0.0016	60.00	0.26
31.1-32.6 m (102-107 ft)	0.08	3	6	-0.39	2.88	1.31	4.56	0.032	75.00	0.26

32.6-34.1 m (107-112 ft)	0.003	0.04	0.14	33.7	4.12	-0.13	1.93	0.0015	46.67	0.26
34.1-35.4 m (112-116 ft)	0.015	0.075	0.095	4.21	2.36	0.51	1.51	0.012	6.33	0.34
35.4-42.1 m (116-138 ft)	0.04	0.32	0.35	2.25	2.98	0.59	1.38	0.03	8.75	0.31
42.1-45.1 m (138-148 ft)	0.0028	0.012	0.015	4.41	4.29	-0.48	1.75	0.0018	5.36	0.35
46.9-49.4 m (154-162 ft)	0.002	0.014	0.04	5.13	3.42	-0.41	2	0.0014	20.00	0.26
49.4-54.7 m (162-179.5 ft)	0.01	0.12	0.14	4.04	3.21	0.33	0.66	0.005	14.00	0.27
Higginsville section										
3.7 m (12-12.3 ft)	0.003	0.015	0.018	5.98	2.31	-1.13	4.75	0.002	6.00	0.34
3.7-3.8 m (12.3-12.5 ft)	0.004	0.014	0.017	6.29	2.2	-0.4	1.28	0.003	4.25	0.37
3.8-3.9 m (12.5-12.8 ft)	0.004	0.009	0.012	6.72	1.83	-0.75	2.66	0.003	3.00	0.40
3.9-4.0 m (12.8-13 ft)	0.00025	0.00045	0.0005	10.4	2.82	-2.97	10.81	0.0002	2.00	0.43
4.0 m (13-13.2 ft)	0.00025	0.0006	0.001	8.08	4.9	-0.95	2.14	0.0002	4.00	0.38
4.0-4.1 m (13.2-13.5 ft)	0.004	0.03	0.04	4.53	2.7	-1.13	4.06	0.003	10.00	0.30
4.1-4.2 m (13.5-13.7 ft)	0.003	0.02	0.03	5.3	2.73	-0.6	3.18	0.002	10.00	0.30
4.2 m (13.7-13.9 ft)	0.0007	0.025	0.06	4.44	4.6	-0.2	1.69	0.0004	85.71	0.26
4.2-4.3 m (13.9-14.1 ft)	0.0014	0.02	0.03	4.96	3.99	-0.65	2.42	0.0006	21.43	0.26
4.3-4.4 m (14.1-14.3 ft)	0.0014	0.018	0.025	5.35	3.61	-0.79	2.94	0.0006	17.86	0.26
4.4 m (14.3-14.5 ft)	0.0015	0.02	0.04	4.85	3.71	-0.63	2.49	0.0007	26.67	0.26
4.4-4.5 m (14.5-14.8 ft)	0.0017	0.02	0.03	4.85	3.74	-0.73	2.54	0.0009	17.65	0.27
4.5-4.6 m (14.8-15 ft)	0.001	0.018	0.03	5.25	4.04	-0.65	2.4	0.0005	30.00	0.26
4.6 m (15-15.2 ft)	0.001	0.018	0.03	5.22	4.42	-0.63	2.22	0.0004	30.00	0.26
4.6-4.7 m (15.2-15.3 ft)	0.001	0.009	0.015	7.03	3.68	-0.07	0.33	0.0006	15.00	0.27
4.7 m (15.3-15.5 ft)	0.0004	0.001	0.005	5.92	6.05	-0.51	1.43	0.0003	12.50	0.28
4.7-4.8 m (15.5-15.6 ft)	0.002	0.0045	0.006	7.45	2.19	-0.54	1.76	0.0015	3.00	0.40

APPENDIX E

Hydraulic Properties

The hydraulic properties of sediments from the Glasford deglacial unit, including K-values for each hydrofacies assemblage and average K-values for the deglacial unit are in the below table.

Table E.1. Hydraulic conductivities calculated by six empirical equations. The hydrogeological data is discussed in Chapter 3 for examined cores presented in Chapter 2. The highlighted cells contain the most appropriate K-value for each sample.

	Hydraulic Conductivity (K)					
Sample Identity	**m/day**	**cm/s**	**m/s**	**ft/day**	**ft/s**	**Empirical Method**
Borehole CHAM-08-05						
30.2-38.7 m (99-127 ft)	8.93E-04	1.03E-06	1.03E-08	2.93E-03	3.39E-08	Kozeny-Carman
30.2-38.7 m (99-127 ft)	2.75E-03	3.18E-06	3.18E-08	9.02E-03	1.04E-07	Breyer
30.2-38.7 m (99-127 ft)	4.00E-04	4.63E-07	4.63E-09	1.31E-03	1.52E-08	Slitcher
30.2-38.7 m (99-127 ft)	5.82E-04	6.73E-07	6.73E-09	1.91E-03	2.21E-08	Terzaghi
30.2-38.7 m (99-127 ft)	3.12E-03	3.61E-06	3.61E-08	1.02E-02	1.19E-07	Alyamani & Sen
30.2-38.7 m (99-127 ft)	2.01E-03	2.33E-06	2.33E-08	6.60E-03	7.64E-08	Hazen
Borehole CHAM-08-07A						
20.0-24.1 m (65-79 ft)	3.33E-03	3.85E-06	3.85E-08	1.09E-02	1.26E-07	Kozeny-Carman
20.0-24.1 m (65-79 ft)	8.04E-03	9.31E-06	9.31E-08	2.64E-02	3.05E-07	Breyer
20.0-24.1 m (65-79 ft)	1.50E-03	1.74E-06	1.74E-08	4.93E-03	5.70E-08	Slitcher
20.0-24.1 m (65-79 ft)	2.14E-03	2.48E-06	2.48E-08	7.03E-03	8.13E-08	Terzaghi
20.0-24.1 m (65-79 ft)	4.15E-02	4.80E-05	4.80E-07	1.36E-01	1.58E-06	Alyamani & Sen
20.0-24.1 m (65-79 ft)	7.64E-03	8.85E-06	8.85E-08	2.51E-02	2.90E-07	Hazen
Borehole FOOSLAND						
33.8-35.7 m (111-117 ft)	8.63E+00	9.99E-03	9.99E-05	2.83E+01	3.28E-04	Kozeny-Carman
33.8-35.7 m (111-117 ft)	2.62E+01	3.03E-02	3.03E-04	8.58E+01	9.93E-04	Breyer
33.8-35.7 m (111-117 ft)	3.88E+00	4.50E-03	4.50E-05	1.27E+01	1.47E-04	Slitcher
33.8-35.7 m (111-117 ft)	5.60E+00	6.48E-03	6.48E-05	1.84E+01	2.12E-04	Terzaghi
33.8-35.7 m (111-117 ft)	3.76E+01	4.35E-02	4.35E-04	1.23E+02	1.43E-03	Alyamani & Sen
33.8-35.7 m (111-117 ft)	1.96E+01	2.27E-02	2.27E-04	6.44E+01	7.46E-04	Hazen
35.6-36.6 m (117-120 ft)	3.32E-03	3.85E-06	3.85E-08	1.09E-02	1.26E-07	Kozeny-Carman
35.6-36.6 m (117-120 ft)	5.62E-03	6.51E-06	6.51E-08	1.84E-02	2.13E-07	Breyer
35.6-36.6 m (117-120 ft)	1.50E-03	1.74E-06	1.74E-08	4.93E-03	5.70E-08	Slitcher
35.6-36.6 m (117-120 ft)	2.14E-03	2.48E-06	2.48E-08	7.02E-03	8.13E-08	Terzaghi
35.6-36.6 m (117-120 ft)	1.15E-01	1.33E-04	1.33E-06	3.77E-01	4.36E-06	Alyamani & Sen
35.6-36.6 m (117-120 ft)	7.64E-03	8.84E-06	8.84E-08	2.51E-02	2.90E-07	Hazen
36.6-41.2 m (120-135 ft)	4.67E-02	5.41E-05	5.41E-07	1.53E-01	1.78E-06	Kozeny-Carman
36.6-41.2 m (120-135 ft)	3.74E-02	4.33E-05	4.33E-07	1.23E-01	1.42E-06	Breyer
36.6-41.2 m (120-135 ft)	2.11E-02	2.44E-05	2.44E-07	6.93E-02	8.02E-07	Slitcher
36.6-41.2 m (120-135 ft)	3.01E-02	3.48E-05	3.48E-07	9.88E-02	1.14E-06	Terzaghi
36.6-41.2 m (120-135 ft)	2.89E+00	3.34E-03	3.34E-05	9.47E+00	1.10E-04	Alyamani & Sen
36.6-41.2 m (120-135 ft)	1.07E-01	1.24E-04	1.24E-06	3.53E-01	4.08E-06	Hazen
41.1-43.3 m (135-142 ft)	1.38E-03	1.60E-06	1.60E-08	4.54E-03	5.26E-08	Kozeny-Carman
41.1-43.3 m (135-142 ft)	2.40E-03	2.77E-06	2.77E-08	7.86E-03	9.10E-08	Breyer

41.1-43.3 m (135-142 ft)	5.48E-04	6.34E-07	6.34E-09	1.80E-03	2.08E-08	Slitcher
41.1-43.3 m (135-142 ft)	9.17E-04	1.06E-06	1.06E-08	3.01E-03	3.48E-08	Terzaghi
41.1-43.3 m (135-142 ft)	1.76E-03	2.03E-06	2.03E-08	5.76E-03	6.67E-08	Alyamani & Sen
41.1-43.3 m (135-142 ft)	2.16E-03	2.50E-06	2.50E-08	7.08E-03	8.19E-08	Hazen
43.3-45.7 m (142-150 ft)	1.98E-02	2.29E-05	2.29E-07	6.49E-02	7.51E-07	Kozeny-Carman
43.3-45.7 m (142-150 ft)	6.05E-02	7.01E-05	7.01E-07	1.99E-01	2.30E-06	Breyer
43.3-45.7 m (142-150 ft)	8.88E-03	1.03E-05	1.03E-07	2.91E-02	3.37E-07	Slitcher
43.3-45.7 m (142-150 ft)	1.28E-02	1.49E-05	1.49E-07	4.21E-02	4.88E-07	Terzaghi
43.3-45.7 m (142-150 ft)	1.24E-01	1.43E-04	1.43E-06	4.06E-01	4.70E-06	Alyamani & Sen
43.3-45.7 m (142-150 ft)	4.48E-02	5.18E-05	5.18E-07	1.47E-01	1.70E-06	Hazen
45.7-46.3 m (150-152 ft)	5.07E+01	5.86E-02	5.86E-04	1.66E+02	1.92E-03	Kozeny-Carman
45.7-46.3 m (150-152 ft)	3.20E+01	3.71E-02	3.71E-04	1.05E+02	1.22E-03	Breyer
45.7-46.3 m (150-152 ft)	1.49E+01	1.73E-02	1.73E-04	4.90E+01	5.67E-04	Slitcher
45.7-46.3 m (150-152 ft)	2.64E+01	3.05E-02	3.05E-04	8.65E+01	1.00E-03	Terzaghi
45.7-46.3 m (150-152 ft)	2.61E+01	3.02E-02	3.02E-04	8.57E+01	9.92E-04	Alyamani & Sen
45.7-46.3 m (150-152 ft)	3.66E+01	4.24E-02	4.24E-04	1.20E+02	1.39E-03	Hazen
46.3-46.6 m (152-153 ft)	1.04E-03	1.20E-06	1.20E-08	3.40E-03	3.93E-08	Kozeny-Carman
46.3-46.6 m (152-153 ft)	3.17E-03	3.67E-06	3.67E-08	1.04E-02	1.20E-07	Breyer
46.3-46.6 m (152-153 ft)	4.61E-04	5.34E-07	5.34E-09	1.51E-03	1.75E-08	Slitcher
46.3-46.6 m (152-153 ft)	6.79E-04	7.86E-07	7.86E-09	2.23E-03	2.58E-08	Terzaghi
46.3-46.6 m (152-153 ft)	3.21E-03	3.72E-06	3.72E-08	1.05E-02	1.22E-07	Alyamani & Sen
46.3-46.6 m (152-153 ft)	2.30E-03	2.66E-06	2.66E-08	7.53E-03	8.72E-08	Hazen
46.6-48.8 m (153-160 ft)	2.55E+00	2.95E-03	2.95E-05	8.36E+00	9.67E-05	Kozeny-Carman
46.6-48.8 m (153-160 ft)	2.66E+00	3.08E-03	3.08E-05	8.74E+00	1.01E-04	Breyer
46.6-48.8 m (153-160 ft)	8.89E-01	1.03E-03	1.03E-05	2.92E+00	3.37E-05	Slitcher
46.6-48.8 m (153-160 ft)	1.54E+00	1.79E-03	1.79E-05	5.07E+00	5.87E-05	Terzaghi
46.6-48.8 m (153-160 ft)	2.21E+00	2.56E-03	2.56E-05	7.26E+00	8.40E-05	Alyamani & Sen
46.6-48.8 m (153-160 ft)	2.79E+00	3.23E-03	3.23E-05	9.17E+00	1.06E-04	Hazen
48.8-50.6 m (160-166 ft)	1.42E+00	1.64E-03	1.64E-05	4.65E+00	5.38E-05	Kozeny-Carman
48.8-50.6 m (160-166 ft)	1.53E+00	1.77E-03	1.77E-05	5.01E+00	5.80E-05	Breyer
48.8-50.6 m (160-166 ft)	4.98E-01	5.77E-04	5.77E-06	1.64E+00	1.89E-05	Slitcher
48.8-50.6 m (160-166 ft)	8.65E-01	1.00E-03	1.00E-05	2.84E+00	3.29E-05	Terzaghi
48.8-50.6 m (160-166 ft)	1.34E+00	1.55E-03	1.55E-05	4.38E+00	5.07E-05	Alyamani & Sen
48.8-50.6 m (160-166 ft)	1.59E+00	1.84E-03	1.84E-05	5.22E+00	6.04E-05	Hazen
50.6-52.1 m (166-171 ft)	2.75E+01	3.19E-02	3.19E-04	9.03E+01	1.05E-03	Kozeny-Carman
50.6-52.1 m (166-171 ft)	2.00E+01	2.32E-02	2.32E-04	6.57E+01	7.61E-04	Breyer
50.6-52.1 m (166-171 ft)	8.56E+00	9.91E-03	9.91E-05	2.81E+01	3.25E-04	Slitcher
50.6-52.1 m (166-171 ft)	1.51E+01	1.74E-02	1.74E-04	4.94E+01	5.72E-04	Terzaghi
50.6-52.1 m (166-171 ft)	1.39E+01	1.60E-02	1.60E-04	4.55E+01	5.26E-04	Alyamani & Sen
50.6-52.1 m (166-171 ft)	2.26E+01	2.61E-02	2.61E-04	7.41E+01	8.58E-04	Hazen
52.1-52.4 m (171-172 ft)	1.31E+01	1.51E-02	1.51E-04	4.29E+01	4.96E-04	Kozeny-Carman
52.1-52.4 m (171-172 ft)	9.58E+00	1.11E-02	1.11E-04	3.14E+01	3.64E-04	Breyer
52.1-52.4 m (171-172 ft)	4.07E+00	4.71E-03	4.71E-05	1.34E+01	1.55E-04	Slitcher
52.1-52.4 m (171-172 ft)	7.17E+00	8.30E-03	8.30E-05	2.35E+01	2.72E-04	Terzaghi
52.1-52.4 m (171-172 ft)	7.85E+00	9.08E-03	9.08E-05	2.57E+01	2.98E-04	Alyamani & Sen
52.1-52.4 m (171-172 ft)	1.08E+01	1.25E-02	1.25E-04	3.54E+01	4.10E-04	Hazen
52.4-53.0 m (172-174 ft)	7.14E+00	8.26E-03	8.26E-05	2.34E+01	2.71E-04	Kozeny-Carman
52.4-53.0 m (172-174 ft)	8.37E+00	9.69E-03	9.69E-05	2.75E+01	3.18E-04	Breyer
52.4-53.0 m (172-174 ft)	2.57E+00	2.97E-03	2.97E-05	8.43E+00	9.76E-05	Slitcher
52.4-53.0 m (172-174 ft)	4.44E+00	5.14E-03	5.14E-05	1.46E+01	1.69E-04	Terzaghi

52.4-53.0 m (172-174 ft)	7.66E+00	8.86E-03	8.86E-05	2.51E+01	2.91E-04	Alyamani & Sen
52.4-53.0 m (172-174 ft)	8.53E+00	9.87E-03	9.87E-05	2.80E+01	3.24E-04	Hazen
53.0-53.9 m (174-177 ft)	1.33E-03	1.54E-06	1.54E-08	4.37E-03	5.06E-08	Kozeny-Carman
53.0-53.9 m (174-177 ft)	2.15E-03	2.48E-06	2.48E-08	7.04E-03	8.15E-08	Breyer
53.0-53.9 m (174-177 ft)	5.19E-04	6.00E-07	6.00E-09	1.70E-03	1.97E-08	Slitcher
53.0-53.9 m (174-177 ft)	8.75E-04	1.01E-06	1.01E-08	2.87E-03	3.32E-08	Terzaghi
53.0-53.9 m (174-177 ft)	1.72E-03	1.99E-06	1.99E-08	5.64E-03	6.53E-08	Alyamani & Sen
53.0-53.9 m (174-177 ft)	1.98E-03	2.29E-06	2.29E-08	6.50E-03	7.52E-08	Hazen
53.9-54.3 m (177-178 ft)	5.30E-02	6.14E-05	6.14E-07	1.74E-01	2.01E-06	Kozeny-Carman
53.9-54.3 m (177-178 ft)	9.32E-02	1.08E-04	1.08E-06	3.06E-01	3.54E-06	Breyer
53.9-54.3 m (177-178 ft)	2.10E-02	2.43E-05	2.43E-07	6.90E-02	7.99E-07	Slitcher
53.9-54.3 m (177-178 ft)	3.52E-02	4.07E-05	4.07E-07	1.15E-01	1.34E-06	Terzaghi
53.9-54.3 m (177-178 ft)	7.81E-02	9.04E-05	9.04E-07	2.56E-01	2.96E-06	Alyamani & Sen
53.9-54.3 m (177-178 ft)	8.34E-02	9.66E-05	9.66E-07	2.74E-01	3.17E-06	Hazen
Borehole FORD-08-01A						
16.8-20.4 m (55-67 ft)	1.19E+00	1.38E-03	1.38E-05	3.91E+00	4.53E-05	Kozeny-Carman
16.8-20.4 m (55-67 ft)	3.61E+00	4.18E-03	4.18E-05	1.18E+01	1.37E-04	Breyer
16.8-20.4 m (55-67 ft)	5.29E-01	6.12E-04	6.12E-06	1.74E+00	2.01E-05	Slitcher
16.8-20.4 m (55-67 ft)	7.85E-01	9.09E-04	9.09E-06	2.58E+00	2.98E-05	Terzaghi
16.8-20.4 m (55-67 ft)	6.06E+00	7.01E-03	7.01E-05	1.99E+01	2.30E-04	Alyamani & Sen
16.8-20.4 m (55-67 ft)	2.61E+00	3.03E-03	3.03E-05	8.58E+00	9.93E-05	Hazen
20.4-24.7 m (67-81 ft)	1.15E-03	1.33E-06	1.33E-08	3.76E-03	4.35E-08	Kozeny-Carman
20.4-24.7 m (67-81 ft)	3.50E-03	4.05E-06	4.05E-08	1.15E-02	1.33E-07	Breyer
20.4-24.7 m (67-81 ft)	5.10E-04	5.91E-07	5.91E-09	1.67E-03	1.94E-08	Slitcher
20.4-24.7 m (67-81 ft)	7.53E-04	8.71E-07	8.71E-09	2.47E-03	2.86E-08	Terzaghi
20.4-24.7 m (67-81 ft)	3.31E-03	3.83E-06	3.83E-08	1.09E-02	1.26E-07	Alyamani & Sen
20.4-24.7 m (67-81 ft)	2.54E-03	2.93E-06	2.93E-08	8.32E-03	9.63E-08	Hazen
24.7-27.6m (81-90.5 ft)	1.70E+01	1.97E-02	1.97E-04	5.58E+01	6.46E-04	Kozeny-Carman
24.7-27.6m (81-90.5 ft)	1.80E+01	2.08E-02	2.08E-04	5.89E+01	6.82E-04	Breyer
24.7-27.6m (81-90.5 ft)	5.95E+00	6.89E-03	6.89E-05	1.95E+01	2.26E-04	Slitcher
24.7-27.6m (81-90.5 ft)	1.03E+01	1.20E-02	1.20E-04	3.39E+01	3.93E-04	Terzaghi
24.7-27.6m (81-90.5 ft)	1.36E+01	1.57E-02	1.57E-04	4.46E+01	5.16E-04	Alyamani & Sen
24.7-27.6m (81-90.5 ft)	1.88E+01	2.18E-02	2.18E-04	6.17E+01	7.14E-04	Hazen
27.6-28.2 m (90.5-92.5 ft)	6.26E-01	7.25E-04	7.25E-06	2.05E+00	2.38E-05	Kozeny-Carman
27.6-28.2 m (90.5-92.5 ft)	1.29E+00	1.49E-03	1.49E-05	4.22E+00	4.89E-05	Breyer
27.6-28.2 m (90.5-92.5 ft)	2.57E-01	2.97E-04	2.97E-06	8.43E-01	9.75E-06	Slitcher
27.6-28.2 m (90.5-92.5 ft)	4.20E-01	4.87E-04	4.87E-06	1.38E+00	1.60E-05	Terzaghi
27.6-28.2 m (90.5-92.5 ft)	8.82E-01	1.02E-03	1.02E-05	2.89E+00	3.35E-05	Alyamani & Sen
27.6-28.2 m (90.5-92.5 ft)	1.09E+00	1.26E-03	1.26E-05	3.57E+00	4.13E-05	Hazen
28.2-29.6 m (92.5-97.0 ft)	1.31E+01	1.52E-02	1.52E-04	4.30E+01	4.98E-04	Kozeny-Carman
28.2-29.6 m (92.5-97.0 ft)	1.50E+01	1.73E-02	1.73E-04	4.92E+01	5.69E-04	Breyer
28.2-29.6 m (92.5-97.0 ft)	4.69E+00	5.43E-03	5.43E-05	1.54E+01	1.78E-04	Slitcher
28.2-29.6 m (92.5-97.0 ft)	8.12E+00	9.39E-03	9.39E-05	2.66E+01	3.08E-04	Terzaghi
28.2-29.6 m (92.5-97.0 ft)	8.01E+00	9.27E-03	9.27E-05	2.63E+01	3.04E-04	Alyamani & Sen
28.2-29.6 m (92.5-97.0 ft)	1.54E+01	1.78E-02	1.78E-04	5.04E+01	5.84E-04	Hazen
29.6-32.6 m (97-107 ft)	1.49E+01	1.72E-02	1.72E-04	4.88E+01	5.64E-04	Kozeny-Carman
29.6-32.6 m (97-107 ft)	1.54E+01	1.78E-02	1.78E-04	5.05E+01	5.84E-04	Breyer
29.6-32.6 m (97-107 ft)	5.17E+00	5.98E-03	5.98E-05	1.70E+01	1.96E-04	Slitcher
29.6-32.6 m (97-107 ft)	8.99E+00	1.04E-02	1.04E-04	2.95E+01	3.41E-04	Terzaghi
29.6-32.6 m (97-107 ft)	9.78E+00	1.13E-02	1.13E-04	3.21E+01	3.71E-04	Alyamani & Sen

29.6-32.6 m (97-107 ft)	1.62E+01	1.87E-02	1.87E-04	5.31E+01	6.14E-04	Hazen
32.6-35.1 m (107 -115 ft)	2.22E-01	2.57E-04	2.57E-06	7.29E-01	8.44E-06	Kozeny-Carman
32.6-35.1 m (107 -115 ft)	6.68E-01	7.74E-04	7.74E-06	2.19E+00	2.54E-05	Breyer
32.6-35.1 m (107 -115 ft)	9.84E-02	1.14E-04	1.14E-06	3.23E-01	3.74E-06	Slitcher
32.6-35.1 m (107 -115 ft)	1.47E-01	1.70E-04	1.70E-06	4.81E-01	5.56E-06	Terzaghi
32.6-35.1 m (107 -115 ft)	9.83E-01	1.14E-03	1.14E-05	3.23E+00	3.73E-05	Alyamani & Sen
32.6-35.1 m (107 -115 ft)	4.85E-01	5.61E-04	5.61E-06	1.59E+00	1.84E-05	Hazen
35.1-36.3 m (115-119 ft)	2.68E+02	3.11E-01	3.11E-03	8.81E+02	1.02E-02	Kozeny-Carman
35.1-36.3 m (115-119 ft)	2.69E+02	3.12E-01	3.12E-03	8.84E+02	1.02E-02	Breyer
35.1-36.3 m (115-119 ft)	9.25E+01	1.07E-01	1.07E-03	3.04E+02	3.51E-03	Slitcher
35.1-36.3 m (115-119 ft)	1.61E+02	1.87E-01	1.87E-03	5.29E+02	6.12E-03	Terzaghi
35.1-36.3 m (115-119 ft)	2.29E+02	2.65E-01	2.65E-03	7.52E+02	8.71E-03	Alyamani & Sen
35.1-36.3 m (115-119 ft)	2.85E+02	3.30E-01	3.30E-03	9.36E+02	1.08E-02	Hazen
Borehole CHAM-09-07						
10.7-11.6 m (35-38 ft)	7.48E-03	8.66E-06	8.66E-08	2.45E-02	2.84E-07	Kozeny-Carman
10.7-11.6 m (35-38 ft)	7.20E-03	8.34E-06	8.34E-08	2.36E-02	2.73E-07	Breyer
10.7-11.6 m (35-38 ft)	3.38E-03	3.91E-06	3.91E-08	1.11E-02	1.28E-07	Slitcher
10.7-11.6 m (35-38 ft)	4.82E-03	5.58E-06	5.58E-08	1.58E-02	1.83E-07	Terzaghi
10.7-11.6 m (35-38 ft)	6.21E-01	7.18E-04	7.18E-06	2.04E+00	2.36E-05	Alyamani & Sen
10.7-11.6 m (35-38 ft)	1.72E-02	1.99E-05	1.99E-07	5.64E-02	6.53E-07	Hazen
11.6-13.9 m (38-45.5 ft)	2.43E-03	2.82E-06	2.82E-08	7.98E-03	9.24E-08	Kozeny-Carman
11.6-13.9 m (38-45.5 ft)	6.98E-03	8.08E-06	8.08E-08	2.29E-02	2.65E-07	Breyer
11.6-13.9 m (38-45.5 ft)	1.07E-03	1.23E-06	1.23E-08	3.50E-03	4.05E-08	Slitcher
11.6-13.9 m (38-45.5 ft)	1.62E-03	1.87E-06	1.87E-08	5.31E-03	6.15E-08	Terzaghi
11.6-13.9 m (38-45.5 ft)	3.58E-04	4.15E-07	4.15E-09	1.18E-03	1.36E-08	Alyamani & Sen
11.6-13.9 m (38-45.5 ft)	5.14E-03	5.95E-06	5.95E-08	1.69E-02	1.95E-07	Hazen
13.9-14.2 m (45.5-46.5 ft)	1.11E-02	1.28E-05	1.28E-07	3.63E-02	4.20E-07	Kozeny-Carman
13.9-14.2 m (45.5-46.5 ft)	2.36E-02	2.73E-05	2.73E-07	7.74E-02	8.96E-07	Breyer
13.9-14.2 m (45.5-46.5 ft)	5.00E-03	5.79E-06	5.79E-08	1.64E-02	1.90E-07	Slitcher
13.9-14.2 m (45.5-46.5 ft)	7.13E-03	8.25E-06	8.25E-08	2.34E-02	2.71E-07	Terzaghi
13.9-14.2 m (45.5-46.5 ft)	2.00E-01	2.32E-04	2.32E-06	6.58E-01	7.61E-06	Alyamani & Sen
13.9-14.2 m (45.5-46.5 ft)	2.55E-02	2.95E-05	2.95E-07	8.35E-02	9.66E-07	Hazen
14.2-14.5 m (46.5-47.5 ft)	2.13E-03	2.46E-06	2.46E-08	6.98E-03	8.07E-08	Kozeny-Carman
14.2-14.5 m (46.5-47.5 ft)	6.50E-03	7.52E-06	7.52E-08	2.13E-02	2.47E-07	Breyer
14.2-14.5 m (46.5-47.5 ft)	9.47E-04	1.10E-06	1.10E-08	3.11E-03	3.60E-08	Slitcher
14.2-14.5 m (46.5-47.5 ft)	1.40E-03	1.61E-06	1.61E-08	4.58E-03	5.30E-08	Terzaghi
14.2-14.5 m (46.5-47.5 ft)	9.30E-03	1.08E-05	1.08E-07	3.05E-02	3.53E-07	Alyamani & Sen
14.2-14.5 m (46.5-47.5 ft)	4.71E-03	5.45E-06	5.45E-08	1.54E-02	1.79E-07	Hazen
14.5-16.9 m (47.5-55.5 ft)	8.10E+01	9.37E-02	9.37E-04	2.66E+02	3.08E-03	Kozeny-Carman
14.5-16.9 m (47.5-55.5 ft)	9.35E+01	1.08E-01	1.08E-03	3.07E+02	3.55E-03	Breyer
14.5-16.9 m (47.5-55.5 ft)	2.90E+01	3.36E-02	3.36E-04	9.52E+01	1.10E-03	Slitcher
14.5-16.9 m (47.5-55.5 ft)	5.02E+01	5.81E-02	5.81E-04	1.65E+02	1.91E-03	Terzaghi
14.5-16.9 m (47.5-55.5 ft)	6.15E+01	7.12E-02	7.12E-04	2.02E+02	2.34E-03	Alyamani & Sen
14.5-16.9 m (47.5-55.5 ft)	9.56E+01	1.11E-01	1.11E-03	3.14E+02	3.63E-03	Hazen
16.9-17.5 m (55.5-57.5 ft)	1.89E+02	2.19E-01	2.19E-03	6.20E+02	7.18E-03	Kozeny-Carman
16.9-17.5 m (55.5-57.5 ft)	1.76E+02	2.04E-01	2.04E-03	5.77E+02	6.68E-03	Breyer
16.9-17.5 m (55.5-57.5 ft)	6.37E+01	7.37E-02	7.37E-04	2.09E+02	2.42E-03	Slitcher
16.9-17.5 m (55.5-57.5 ft)	1.11E+02	1.29E-01	1.29E-03	3.65E+02	4.23E-03	Terzaghi
16.9-17.5 m (55.5-57.5 ft)	1.29E+02	1.49E-01	1.49E-03	4.23E+02	4.90E-03	Alyamani & Sen
16.9-17.5 m (55.5-57.5 ft)	1.90E+02	2.20E-01	2.20E-03	6.22E+02	7.20E-03	Hazen

17.5-18.8 m (57.5-61.5 ft)	1.83E+01	2.12E-02	2.12E-04	6.01E+01	6.96E-04	Kozeny-Carman
17.5-18.8 m (57.5-61.5 ft)	3.61E+01	4.18E-02	4.18E-04	1.18E+02	1.37E-03	Breyer
17.5-18.8 m (57.5-61.5 ft)	7.45E+00	8.62E-03	8.62E-05	2.44E+01	2.83E-04	Slitcher
17.5-18.8 m (57.5-61.5 ft)	1.23E+01	1.42E-02	1.42E-04	4.03E+01	4.66E-04	Terzaghi
17.5-18.8 m (57.5-61.5 ft)	3.98E+01	4.61E-02	4.61E-04	1.31E+02	1.51E-03	Alyamani & Sen
17.5-18.8 m (57.5-61.5 ft)	3.10E+01	3.59E-02	3.59E-04	1.02E+02	1.18E-03	Hazen
22.9-25.7 m (75-84.2 ft)	2.46E+02	2.84E-01	2.84E-03	8.06E+02	9.33E-03	Kozeny-Carman
22.9-25.7 m (75-84.2 ft)	1.87E+02	2.16E-01	2.16E-03	6.13E+02	7.10E-03	Breyer
22.9-25.7 m (75-84.2 ft)	7.76E+01	8.98E-02	8.98E-04	2.54E+02	2.95E-03	Slitcher
22.9-25.7 m (75-84.2 ft)	1.36E+02	1.58E-01	1.58E-03	4.48E+02	5.18E-03	Terzaghi
22.9-25.7 m (75-84.2 ft)	1.44E+02	1.66E-01	1.66E-03	4.72E+02	5.46E-03	Alyamani & Sen
22.9-25.7 m (75-84.2 ft)	2.09E+02	2.42E-01	2.42E-03	6.87E+02	7.95E-03	Hazen
27.4-30.5 m (90-100 ft)	2.55E+00	2.95E-03	2.95E-05	8.36E+00	9.67E-05	Kozeny-Carman
27.4-30.5 m (90-100 ft)	2.66E+00	3.08E-03	3.08E-05	8.74E+00	1.01E-04	Breyer
27.4-30.5 m (90-100 ft)	8.89E-01	1.03E-03	1.03E-05	2.92E+00	3.37E-05	Slitcher
27.4-30.5 m (90-100 ft)	1.54E+00	1.79E-03	1.79E-05	5.07E+00	5.87E-05	Terzaghi
27.4-30.5 m (90-100 ft)	2.43E+00	2.81E-03	2.81E-05	7.98E+00	9.23E-05	Alyamani & Sen
27.4-30.5 m (90-100 ft)	2.79E+00	3.23E-03	3.23E-05	9.17E+00	1.06E-04	Hazen
30.5-33.5 m (100-110 ft)	2.64E+01	3.06E-02	3.06E-04	8.67E+01	1.00E-03	Kozeny-Carman
30.5-33.5 m (100-110 ft)	2.73E+01	3.17E-02	3.17E-04	8.97E+01	1.04E-03	Breyer
30.5-33.5 m (100-110 ft)	9.19E+00	1.06E-02	1.06E-04	3.02E+01	3.49E-04	Slitcher
30.5-33.5 m (100-110 ft)	1.60E+01	1.85E-02	1.85E-04	5.25E+01	6.07E-04	Terzaghi
30.5-33.5 m (100-110 ft)	2.15E+01	2.48E-02	2.48E-04	7.04E+01	8.15E-04	Alyamani & Sen
30.5-33.5 m (100-110 ft)	2.88E+01	3.33E-02	3.33E-04	9.44E+01	1.09E-03	Hazen
33.5-36.6 m (110-120 ft)	7.55E+00	8.74E-03	8.74E-05	2.48E+01	2.87E-04	Kozeny-Carman
33.5-36.6 m (110-120 ft)	6.76E+00	7.83E-03	7.83E-05	2.22E+01	2.57E-04	Breyer
33.5-36.6 m (110-120 ft)	2.52E+00	2.91E-03	2.91E-05	8.25E+00	9.55E-05	Slitcher
33.5-36.6 m (110-120 ft)	4.40E+00	5.09E-03	5.09E-05	1.44E+01	1.67E-04	Terzaghi
33.5-36.6 m (110-120 ft)	6.15E+00	7.12E-03	7.12E-05	2.02E+01	2.34E-04	Alyamani & Sen
33.5-36.6 m (110-120 ft)	7.35E+00	8.51E-03	8.51E-05	2.41E+01	2.79E-04	Hazen
36.6-42.7 m (120-140 ft)	8.07E+00	9.34E-03	9.34E-05	2.65E+01	3.06E-04	Kozeny-Carman
36.6-42.7 m (120-140 ft)	8.59E+00	9.94E-03	9.94E-05	2.82E+01	3.26E-04	Breyer
36.6-42.7 m (120-140 ft)	2.83E+00	3.27E-03	3.27E-05	9.28E+00	1.07E-04	Slitcher
36.6-42.7 m (120-140 ft)	4.91E+00	5.69E-03	5.69E-05	1.61E+01	1.87E-04	Terzaghi
36.6-42.7 m (120-140 ft)	6.88E+00	7.96E-03	7.96E-05	2.26E+01	2.61E-04	Alyamani & Sen
36.6-42.7 m (120-140 ft)	8.97E+00	1.04E-02	1.04E-04	2.94E+01	3.41E-04	Hazen
42.7-44.8 m (140-147 ft)	1.61E+01	1.87E-02	1.87E-04	5.29E+01	6.13E-04	Kozeny-Carman
42.7-44.8 m (140-147 ft)	4.96E+01	5.74E-02	5.74E-04	1.63E+02	1.88E-03	Breyer
42.7-44.8 m (140-147 ft)	7.24E+00	8.38E-03	8.38E-05	2.37E+01	2.75E-04	Slitcher
42.7-44.8 m (140-147 ft)	1.05E+01	1.21E-02	1.21E-04	3.44E+01	3.99E-04	Terzaghi
42.7-44.8 m (140-147 ft)	7.38E+01	8.54E-02	8.54E-04	2.42E+02	2.80E-03	Alyamani & Sen
42.7-44.8 m (140-147 ft)	3.64E+01	4.22E-02	4.22E-04	1.20E+02	1.38E-03	Hazen
Borehole CHAM-07-01A						
30.2-33.5 m (99-110 ft)	1.19E-01	1.38E-04	1.38E-06	3.92E-01	4.53E-06	Kozeny-Carman
30.2-33.5 m (99-110 ft)	3.22E-01	3.73E-04	3.73E-06	1.06E+00	1.22E-05	Breyer
30.2-33.5 m (99-110 ft)	5.16E-02	5.98E-05	5.98E-07	1.69E-01	1.96E-06	Slitcher
30.2-33.5 m (99-110 ft)	8.00E-02	9.25E-05	9.25E-07	2.62E-01	3.04E-06	Terzaghi
30.2-33.5 m (99-110 ft)	4.94E-01	5.72E-04	5.72E-06	1.62E+00	1.88E-05	Alyamani & Sen
30.2-33.5 m (99-110 ft)	2.43E-01	2.82E-04	2.82E-06	7.98E-01	9.24E-06	Hazen
33.5-35.1 m (110-115 ft)	2.56E-03	2.96E-06	2.96E-08	8.38E-03	9.70E-08	Kozeny-Carman

33.5-35.1 m (110-115 ft)	7.12E-03	8.24E-06	8.24E-08	2.34E-02	2.70E-07	Breyer
33.5-35.1 m (110-115 ft)	1.11E-03	1.29E-06	1.29E-08	3.65E-03	4.23E-08	Slitcher
33.5-35.1 m (110-115 ft)	1.71E-03	1.98E-06	1.98E-08	5.60E-03	6.48E-08	Terzaghi
33.5-35.1 m (110-115 ft)	6.88E-03	7.96E-06	7.96E-08	2.26E-02	2.61E-07	Alyamani & Sen
33.5-35.1 m (110-115 ft)	5.31E-03	6.14E-06	6.14E-08	1.74E-02	2.02E-07	Hazen
35.1-36.6 m (115-120 ft)	8.00E-04	9.26E-07	9.26E-09	2.62E-03	3.04E-08	Kozeny-Carman
35.1-36.6 m (115-120 ft)	2.41E-03	2.78E-06	2.78E-08	7.89E-03	9.14E-08	Breyer
35.1-36.6 m (115-120 ft)	3.54E-04	4.10E-07	4.10E-09	1.16E-03	1.35E-08	Slitcher
35.1-36.6 m (115-120 ft)	5.28E-04	6.11E-07	6.11E-09	1.73E-03	2.00E-08	Terzaghi
35.1-36.6 m (115-120 ft)	2.05E-03	2.37E-06	2.37E-08	6.72E-03	7.78E-08	Alyamani & Sen
35.1-36.6 m (115-120 ft)	1.75E-03	2.02E-06	2.02E-08	5.73E-03	6.63E-08	Hazen
36.6-39.6 m (120-130 ft)	3.28E-01	3.79E-04	3.79E-06	1.07E+00	1.24E-05	Kozeny-Carman
36.6-39.6 m (120-130 ft)	7.69E-01	8.90E-04	8.90E-06	2.52E+00	2.92E-05	Breyer
36.6-39.6 m (120-130 ft)	1.38E-01	1.60E-04	1.60E-06	4.53E-01	5.24E-06	Slitcher
36.6-39.6 m (120-130 ft)	2.21E-01	2.55E-04	2.55E-06	7.24E-01	8.38E-06	Terzaghi
36.6-39.6 m (120-130 ft)	7.80E-01	9.03E-04	9.03E-06	2.56E+00	2.96E-05	Alyamani & Sen
36.6-39.6 m (120-130 ft)	6.15E-01	7.12E-04	7.12E-06	2.02E+00	2.34E-05	Hazen
39.6-42.7 m (130-140 ft)	4.77E-01	5.53E-04	5.53E-06	1.57E+00	1.81E-05	Kozeny-Carman
39.6-42.7 m (130-140 ft)	1.29E+00	1.49E-03	1.49E-05	4.23E+00	4.89E-05	Breyer
39.6-42.7 m (130-140 ft)	2.07E-01	2.39E-04	2.39E-06	6.78E-01	7.84E-06	Slitcher
39.6-42.7 m (130-140 ft)	3.20E-01	3.70E-04	3.70E-06	1.05E+00	1.21E-05	Terzaghi
39.6-42.7 m (130-140 ft)	1.50E+00	1.74E-03	1.74E-05	4.93E+00	5.71E-05	Alyamani & Sen
39.6-42.7 m (130-140 ft)	9.73E-01	1.13E-03	1.13E-05	3.19E+00	3.70E-05	Hazen
42.7-44.8 m (140-147 ft)	4.47E+01	5.17E-02	5.17E-04	1.47E+02	1.70E-03	Kozeny-Carman
42.7-44.8 m (140-147 ft)	3.38E+01	3.91E-02	3.91E-04	1.11E+02	1.28E-03	Breyer
42.7-44.8 m (140-147 ft)	1.41E+01	1.63E-02	1.63E-04	4.62E+01	5.35E-04	Slitcher
42.7-44.8 m (140-147 ft)	2.48E+01	2.87E-02	2.87E-04	8.13E+01	9.41E-04	Terzaghi
42.7-44.8 m (140-147 ft)	2.02E+01	2.33E-02	2.33E-04	6.61E+01	7.65E-04	Alyamani & Sen
42.7-44.8 m (140-147 ft)	3.79E+01	4.39E-02	4.39E-04	1.24E+02	1.44E-03	Hazen
44.8-47.6 m (147-156 ft)	4.06E+01	4.70E-02	4.70E-04	1.33E+02	1.54E-03	Kozeny-Carman
44.8-47.6 m (147-156 ft)	2.49E+01	2.88E-02	2.88E-04	8.16E+01	9.44E-04	Breyer
44.8-47.6 m (147-156 ft)	1.18E+01	1.37E-02	1.37E-04	3.87E+01	4.48E-04	Slitcher
44.8-47.6 m (147-156 ft)	2.09E+01	2.42E-02	2.42E-04	6.85E+01	7.92E-04	Terzaghi
44.8-47.6 m (147-156 ft)	1.62E+01	1.87E-02	1.87E-04	5.30E+01	6.14E-04	Alyamani & Sen
44.8-47.6 m (147-156 ft)	2.85E+01	3.29E-02	3.29E-04	9.34E+01	1.08E-03	Hazen
47.6-51.2 m (156-168 ft)	4.34E+02	5.03E-01	5.03E-03	1.42E+03	1.65E-02	Kozeny-Carman
47.6-51.2 m (156-168 ft)	3.01E+02	3.49E-01	3.49E-03	9.89E+02	1.14E-02	Breyer
47.6-51.2 m (156-168 ft)	1.33E+02	1.54E-01	1.54E-03	4.35E+02	5.04E-03	Slitcher
47.6-51.2 m (156-168 ft)	2.34E+02	2.71E-01	2.71E-03	7.67E+02	8.88E-03	Terzaghi
47.6-51.2 m (156-168 ft)	2.16E+02	2.50E-01	2.50E-03	7.08E+02	8.20E-03	Alyamani & Sen
47.6-51.2 m (156-168 ft)	3.42E+02	3.96E-01	3.96E-03	1.12E+03	1.30E-02	Hazen
Borehole CHAM-07-04A						
25.0-31.1 m (82-102 ft)	8.31E-04	9.62E-07	9.62E-09	2.73E-03	3.16E-08	Kozeny-Carman
25.0-31.1 m (82-102 ft)	1.85E-03	2.14E-06	2.14E-08	6.08E-03	7.03E-08	Breyer
25.0-31.1 m (82-102 ft)	3.75E-04	4.35E-07	4.35E-09	1.23E-03	1.43E-08	Slitcher
25.0-31.1 m (82-102 ft)	5.35E-04	6.20E-07	6.20E-09	1.76E-03	2.03E-08	Terzaghi
25.0-31.1 m (82-102 ft)	9.30E-03	1.08E-05	1.08E-07	3.05E-02	3.53E-07	Alyamani & Sen
25.0-31.1 m (82-102 ft)	1.91E-03	2.21E-06	2.21E-08	6.27E-03	7.25E-08	Hazen
31.1-32.6 m (102-107 ft)	1.33E+00	1.54E-03	1.54E-05	4.36E+00	5.05E-05	Kozeny-Carman
31.1-32.6 m (102-107 ft)	2.65E+00	3.07E-03	3.07E-05	8.70E+00	1.01E-04	Breyer

31.1-32.6 m (102-107 ft)	6.01E-01	6.95E-04	6.95E-06	1.97E+00	2.28E-05	Slitcher
31.1-32.6 m (102-107 ft)	8.56E-01	9.91E-04	9.91E-06	2.81E+00	3.25E-05	Terzaghi
31.1-32.6 m (102-107 ft)	1.43E+01	1.66E-02	1.66E-04	4.70E+01	5.44E-04	Alyamani & Sen
31.1-32.6 m (102-107 ft)	3.06E+00	3.54E-03	3.54E-05	1.00E+01	1.16E-04	Hazen
32.6-34.1 m (107-112 ft)	1.87E-03	2.17E-06	2.17E-08	6.14E-03	7.11E-08	Kozeny-Carman
32.6-34.1 m (107-112 ft)	4.66E-03	5.39E-06	5.39E-08	1.53E-02	1.77E-07	Breyer
32.6-34.1 m (107-112 ft)	8.45E-04	9.78E-07	9.78E-09	2.77E-03	3.21E-08	Slitcher
32.6-34.1 m (107-112 ft)	1.21E-03	1.40E-06	1.40E-08	3.95E-03	4.58E-08	Terzaghi
32.6-34.1 m (107-112 ft)	7.64E-03	8.85E-06	8.85E-08	2.51E-02	2.90E-07	Alyamani & Sen
32.6-34.1 m (107-112 ft)	4.30E-03	4.98E-06	4.98E-08	1.41E-02	1.63E-07	Hazen
34.1-35.4 m (112-116 ft)	1.33E-01	1.54E-04	1.54E-06	4.37E-01	5.06E-06	Kozeny-Carman
34.1-35.4 m (112-116 ft)	2.15E-01	2.48E-04	2.48E-06	7.04E-01	8.15E-06	Breyer
34.1-35.4 m (112-116 ft)	5.19E-02	6.00E-05	6.00E-07	1.70E-01	1.97E-06	Slitcher
34.1-35.4 m (112-116 ft)	8.75E-02	1.01E-04	1.01E-06	2.87E-01	3.32E-06	Terzaghi
34.1-35.4 m (112-116 ft)	2.37E-01	2.74E-04	2.74E-06	7.77E-01	9.00E-06	Alyamani & Sen
34.1-35.4 m (112-116 ft)	1.98E-01	2.29E-04	2.29E-06	6.50E-01	7.52E-06	Hazen
35.4-42.1 m (116-138 ft)	6.67E-01	7.71E-04	7.71E-06	2.19E+00	2.53E-05	Kozeny-Carman
35.4-42.1 m (116-138 ft)	1.41E+00	1.64E-03	1.64E-05	4.64E+00	5.37E-05	Breyer
35.4-42.1 m (116-138 ft)	2.75E-01	3.18E-04	3.18E-06	9.02E-01	1.04E-05	Slitcher
35.4-42.1 m (116-138 ft)	4.48E-01	5.19E-04	5.19E-06	1.47E+00	1.70E-05	Terzaghi
35.4-42.1 m (116-138 ft)	1.78E+00	2.06E-03	2.06E-05	5.84E+00	6.76E-05	Alyamani & Sen
35.4-42.1 m (116-138 ft)	1.18E+00	1.36E-03	1.36E-05	3.87E+00	4.48E-05	Hazen
42.1-45.1 m (138-148 ft)	5.59E-03	6.46E-06	6.46E-08	1.83E-02	2.12E-07	Kozeny-Carman
42.1-45.1 m (138-148 ft)	7.76E-03	8.99E-06	8.99E-08	2.55E-02	2.95E-07	Breyer
42.1-45.1 m (138-148 ft)	2.10E-03	2.43E-06	2.43E-08	6.89E-03	7.97E-08	Slitcher
42.1-45.1 m (138-148 ft)	3.59E-03	4.15E-06	4.15E-08	1.18E-02	1.36E-07	Terzaghi
42.1-45.1 m (138-148 ft)	5.36E-03	6.20E-06	6.20E-08	1.76E-02	2.03E-07	Alyamani & Sen
42.1-45.1 m (138-148 ft)	7.52E-03	8.70E-06	8.70E-08	2.47E-02	2.86E-07	Hazen
46.9-49.4 m (154-162 ft)	9.13E-04	1.06E-06	1.06E-08	3.00E-03	3.47E-08	Kozeny-Carman
46.9-49.4 m (154-162 ft)	2.81E-03	3.25E-06	3.25E-08	9.22E-03	1.07E-07	Breyer
46.9-49.4 m (154-162 ft)	4.08E-04	4.73E-07	4.73E-09	1.34E-03	1.55E-08	Slitcher
46.9-49.4 m (154-162 ft)	5.97E-04	6.91E-07	6.91E-09	1.96E-03	2.27E-08	Terzaghi
46.9-49.4 m (154-162 ft)	3.76E-03	4.35E-06	4.35E-08	1.23E-02	1.43E-07	Alyamani & Sen
46.9-49.4 m (154-162 ft)	2.04E-03	2.36E-06	2.36E-08	6.70E-03	7.76E-08	Hazen
49.4-54.7 m (162-179.5 ft)	2.74E-02	3.17E-05	3.17E-07	9.00E-02	1.04E-06	Kozeny-Carman
49.4-54.7 m (162-179.5 ft)	7.81E-02	9.04E-05	9.04E-07	2.56E-01	2.96E-06	Breyer
49.4-54.7 m (162-179.5 ft)	1.20E-02	1.39E-05	1.39E-07	3.94E-02	4.55E-07	Slitcher
49.4-54.7 m (162-179.5 ft)	1.83E-02	2.11E-05	2.11E-07	5.99E-02	6.94E-07	Terzaghi
49.4-54.7 m (162-179.5 ft)	7.81E-02	9.04E-05	9.04E-07	2.56E-01	2.96E-06	Alyamani & Sen
49.4-54.7 m (162-179.5 ft)	5.77E-02	6.68E-05	6.68E-07	1.89E-01	2.19E-06	Hazen
Higginsville section						
3.7 m (12-12.3 ft)	5.66E-03	6.55E-06	6.55E-08	1.86E-02	2.15E-07	Kozeny-Carman
3.7 m (12-12.3 ft)	8.69E-03	1.01E-05	1.01E-07	2.85E-02	3.30E-07	Breyer
3.7 m (12-12.3 ft)	2.18E-03	2.52E-06	2.52E-08	7.15E-03	8.27E-08	Slitcher
3.7 m (12-12.3 ft)	3.69E-03	4.27E-06	4.27E-08	1.21E-02	1.40E-07	Terzaghi
3.7 m (12-12.3 ft)	6.88E-03	7.96E-06	7.96E-08	2.26E-02	2.61E-07	Alyamani & Sen
3.7 m (12-12.3 ft)	8.15E-03	9.44E-06	9.44E-08	2.67E-02	3.10E-07	Hazen
3.7-3.8 m (12.3-12.5 ft)	1.46E-02	1.69E-05	1.69E-07	4.78E-02	5.53E-07	Kozeny-Carman
3.7-3.8 m (12.3-12.5 ft)	1.67E-02	1.93E-05	1.93E-07	5.46E-02	6.32E-07	Breyer
3.7-3.8 m (12.3-12.5 ft)	5.21E-03	6.03E-06	6.03E-08	1.71E-02	1.98E-07	Slitcher

3.7-3.8 m (12.3-12.5 ft)	9.02E-03	1.04E-05	1.04E-07	2.96E-02	3.42E-07	Terzaghi
3.7-3.8 m (12.3-12.5 ft)	1.37E-02	1.59E-05	1.59E-07	4.51E-02	5.21E-07	Alyamani & Sen
3.7-3.8 m (12.3-12.5 ft)	1.71E-02	1.98E-05	1.98E-07	5.60E-02	6.48E-07	Hazen
3.8-3.9 m (12.5-12.8 ft)	2.03E-02	2.35E-05	2.35E-07	6.66E-02	7.71E-07	Kozeny-Carman
3.8-3.9 m (12.5-12.8 ft)	1.79E-02	2.07E-05	2.07E-07	5.86E-02	6.79E-07	Breyer
3.8-3.9 m (12.5-12.8 ft)	6.73E-03	7.79E-06	7.79E-08	2.21E-02	2.55E-07	Slitcher
3.8-3.9 m (12.5-12.8 ft)	1.18E-02	1.36E-05	1.36E-07	3.86E-02	4.47E-07	Terzaghi
3.8-3.9 m (12.5-12.8 ft)	1.27E-02	1.47E-05	1.47E-07	4.17E-02	4.82E-07	Alyamani & Sen
3.8-3.9 m (12.5-12.8 ft)	1.95E-02	2.26E-05	2.26E-07	6.40E-02	7.40E-07	Hazen
3.9-4.0 m (12.8-13 ft)	1.09E-04	1.26E-07	1.26E-09	3.56E-04	4.12E-09	Kozeny-Carman
3.9-4.0 m (12.8-13 ft)	7.53E-05	8.72E-08	8.72E-10	2.47E-04	2.86E-09	Breyer
3.9-4.0 m (12.8-13 ft)	3.32E-05	3.84E-08	3.84E-10	1.09E-04	1.26E-09	Slitcher
3.9-4.0 m (12.8-13 ft)	5.85E-05	6.77E-08	6.77E-10	1.92E-04	2.22E-09	Terzaghi
3.9-4.0 m (12.8-13 ft)	5.46E-05	6.32E-08	6.32E-10	1.79E-04	2.07E-09	Alyamani & Sen
3.9-4.0 m (12.8-13 ft)	8.54E-05	9.89E-08	9.89E-10	2.80E-04	3.24E-09	Hazen
4.0 m (13-13.2 ft)	6.05E-05	7.01E-08	7.01E-10	1.99E-04	2.30E-09	Kozeny-Carman
4.0 m (13-13.2 ft)	6.59E-05	7.63E-08	7.63E-10	2.16E-04	2.50E-09	Breyer
4.0 m (13-13.2 ft)	2.14E-05	2.47E-08	2.47E-10	7.01E-05	8.11E-10	Slitcher
4.0 m (13-13.2 ft)	3.71E-05	4.29E-08	4.29E-10	1.22E-04	1.41E-09	Terzaghi
4.0 m (13-13.2 ft)	5.66E-05	6.56E-08	6.56E-10	1.86E-04	2.15E-09	Alyamani & Sen
4.0 m (13-13.2 ft)	6.84E-05	7.92E-08	7.92E-10	2.24E-04	2.60E-09	Hazen
4.0-4.1 m (13.2-13.5 ft)	5.82E-03	6.74E-06	6.74E-08	1.91E-02	2.21E-07	Kozeny-Carman
4.0-4.1 m (13.2-13.5 ft)	1.37E-02	1.58E-05	1.58E-07	4.48E-02	5.19E-07	Breyer
4.0-4.1 m (13.2-13.5 ft)	2.45E-03	2.84E-06	2.84E-08	8.04E-03	9.31E-08	Slitcher
4.0-4.1 m (13.2-13.5 ft)	3.92E-03	4.54E-06	4.54E-08	1.29E-02	1.49E-07	Terzaghi
4.0-4.1 m (13.2-13.5 ft)	1.73E-02	2.00E-05	2.00E-07	5.68E-02	6.58E-07	Alyamani & Sen
4.0-4.1 m (13.2-13.5 ft)	1.09E-02	1.27E-05	1.27E-07	3.59E-02	4.15E-07	Hazen
4.1-4.2 m (13.5-13.7 ft)	3.28E-03	3.79E-06	3.79E-08	1.07E-02	1.24E-07	Kozeny-Carman
4.1-4.2 m (13.5-13.7 ft)	7.69E-03	8.90E-06	8.90E-08	2.52E-02	2.92E-07	Breyer
4.1-4.2 m (13.5-13.7 ft)	1.38E-03	1.60E-06	1.60E-08	4.53E-03	5.24E-08	Slitcher
4.1-4.2 m (13.5-13.7 ft)	2.21E-03	2.55E-06	2.55E-08	7.24E-03	8.38E-08	Terzaghi
4.1-4.2 m (13.5-13.7 ft)	7.64E-03	8.85E-06	8.85E-08	2.51E-02	2.90E-07	Alyamani & Sen
4.1-4.2 m (13.5-13.7 ft)	6.15E-03	7.12E-06	7.12E-08	2.02E-02	2.34E-07	Hazen
4.2 m (13.7-13.9 ft)	1.02E-04	1.18E-07	1.18E-09	3.34E-04	3.87E-09	Kozeny-Carman
4.2 m (13.7-13.9 ft)	1.89E-04	2.18E-07	2.18E-09	6.19E-04	7.16E-09	Breyer
4.2 m (13.7-13.9 ft)	4.60E-05	5.32E-08	5.32E-10	1.51E-04	1.75E-09	Slitcher
4.2 m (13.7-13.9 ft)	6.56E-05	7.59E-08	7.59E-10	2.15E-04	2.49E-09	Terzaghi
4.2 m (13.7-13.9 ft)	1.32E-03	1.53E-06	1.53E-08	4.33E-03	5.01E-08	Alyamani & Sen
4.2 m (13.7-13.9 ft)	2.34E-04	2.71E-07	2.71E-09	7.68E-04	8.89E-09	Hazen
4.2-4.3 m (13.9-14.1 ft)	4.38E-04	5.07E-07	5.07E-09	1.44E-03	1.66E-08	Kozeny-Carman
4.2-4.3 m (13.9-14.1 ft)	1.35E-03	1.56E-06	1.56E-08	4.42E-03	5.12E-08	Breyer
4.2-4.3 m (13.9-14.1 ft)	1.96E-04	2.27E-07	2.27E-09	6.44E-04	7.45E-09	Slitcher
4.2-4.3 m (13.9-14.1 ft)	2.85E-04	3.30E-07	3.30E-09	9.36E-04	1.08E-08	Terzaghi
4.2-4.3 m (13.9-14.1 ft)	1.47E-03	1.71E-06	1.71E-08	4.84E-03	5.60E-08	Alyamani & Sen
4.2-4.3 m (13.9-14.1 ft)	9.86E-04	1.14E-06	1.14E-08	3.24E-03	3.74E-08	Hazen
4.3-4.4 m (14.1-14.3 ft)	4.68E-04	5.42E-07	5.42E-09	1.54E-03	1.78E-08	Kozeny-Carman
4.3-4.4 m (14.1-14.3 ft)	1.43E-03	1.65E-06	1.65E-08	4.68E-03	5.41E-08	Breyer
4.3-4.4 m (14.1-14.3 ft)	2.08E-04	2.41E-07	2.41E-09	6.83E-04	7.90E-09	Slitcher
4.3-4.4 m (14.1-14.3 ft)	3.08E-04	3.56E-07	3.56E-09	1.01E-03	1.17E-08	Terzaghi
4.3-4.4 m (14.1-14.3 ft)	1.34E-03	1.55E-06	1.55E-08	4.39E-03	5.09E-08	Alyamani & Sen

4.3-4.4 m (14.1-14.3 ft)	1.03E-03	1.19E-06	1.19E-08	3.39E-03	3.92E-08	Hazen
4.4 m (14.3-14.5 ft)	4.81E-04	5.56E-07	5.56E-09	1.58E-03	1.83E-08	Kozeny-Carman
4.4 m (14.3-14.5 ft)	1.44E-03	1.67E-06	1.67E-08	4.72E-03	5.47E-08	Breyer
4.4 m (14.3-14.5 ft)	2.17E-04	2.51E-07	2.51E-09	7.10E-04	8.22E-09	Slitcher
4.4 m (14.3-14.5 ft)	3.11E-04	3.60E-07	3.60E-09	1.02E-03	1.18E-08	Terzaghi
4.4 m (14.3-14.5 ft)	1.76E-03	2.03E-06	2.03E-08	5.76E-03	6.67E-08	Alyamani & Sen
4.4 m (14.3-14.5 ft)	1.10E-03	1.27E-06	1.27E-08	3.60E-03	4.16E-08	Hazen
4.4-4.5 m (14.5-14.8 ft)	6.94E-04	8.03E-07	8.03E-09	2.28E-03	2.63E-08	Kozeny-Carman
4.4-4.5 m (14.5-14.8 ft)	2.11E-03	2.44E-06	2.44E-08	6.92E-03	8.01E-08	Breyer
4.4-4.5 m (14.5-14.8 ft)	3.08E-04	3.57E-07	3.57E-09	1.01E-03	1.17E-08	Slitcher
4.4-4.5 m (14.5-14.8 ft)	4.56E-04	5.28E-07	5.28E-09	1.50E-03	1.73E-08	Terzaghi
4.4-4.5 m (14.5-14.8 ft)	2.40E-03	2.77E-06	2.77E-08	7.86E-03	9.10E-08	Alyamani & Sen
4.4-4.5 m (14.5-14.8 ft)	1.53E-03	1.77E-06	1.77E-08	5.01E-03	5.80E-08	Hazen
4.5-4.6 m (14.8-15 ft)	2.11E-04	2.44E-07	2.44E-09	6.92E-04	8.01E-09	Kozeny-Carman
4.5-4.6 m (14.8-15 ft)	6.14E-04	7.11E-07	7.11E-09	2.02E-03	2.33E-08	Breyer
4.5-4.6 m (14.8-15 ft)	9.52E-05	1.10E-07	1.10E-09	3.12E-04	3.61E-09	Slitcher
4.5-4.6 m (14.8-15 ft)	1.36E-04	1.58E-07	1.58E-09	4.47E-04	5.17E-09	Terzaghi
4.5-4.6 m (14.8-15 ft)	1.11E-03	1.29E-06	1.29E-08	3.65E-03	4.22E-08	Alyamani & Sen
4.5-4.6 m (14.8-15 ft)	4.83E-04	5.59E-07	5.59E-09	1.58E-03	1.83E-08	Hazen
4.6 m (15-15.2 ft)	2.11E-04	2.44E-07	2.44E-09	6.92E-04	8.01E-09	Kozeny-Carman
4.6 m (15-15.2 ft)	6.14E-04	7.11E-07	7.11E-09	2.02E-03	2.33E-08	Breyer
4.6 m (15-15.2 ft)	9.52E-05	1.10E-07	1.10E-09	3.12E-04	3.61E-09	Slitcher
4.6 m (15-15.2 ft)	1.36E-04	1.58E-07	1.58E-09	4.47E-04	5.17E-09	Terzaghi
4.6 m (15-15.2 ft)	8.85E-04	1.02E-06	1.02E-08	2.90E-03	3.36E-08	Alyamani & Sen
4.6 m (15-15.2 ft)	4.83E-04	5.59E-07	5.59E-09	1.58E-03	1.83E-08	Hazen
4.6-4.7 m (15.2-15.3 ft)	2.62E-04	3.03E-07	3.03E-09	8.60E-04	9.95E-09	Kozeny-Carman
4.6-4.7 m (15.2-15.3 ft)	7.66E-04	8.86E-07	8.86E-09	2.51E-03	2.91E-08	Breyer
4.6-4.7 m (15.2-15.3 ft)	1.15E-04	1.33E-07	1.33E-09	3.78E-04	4.38E-09	Slitcher
4.6-4.7 m (15.2-15.3 ft)	1.74E-04	2.01E-07	2.01E-09	5.71E-04	6.60E-09	Terzaghi
4.6-4.7 m (15.2-15.3 ft)	8.32E-04	9.63E-07	9.63E-09	2.73E-03	3.16E-08	Alyamani & Sen
4.6-4.7 m (15.2-15.3 ft)	5.60E-04	6.48E-07	6.48E-09	1.84E-03	2.13E-08	Hazen
4.7 m (15.3-15.5 ft)	4.77E-05	5.53E-08	5.53E-10	1.57E-04	1.81E-09	Kozeny-Carman
4.7 m (15.3-15.5 ft)	1.29E-04	1.49E-07	1.49E-09	4.23E-04	4.89E-09	Breyer
4.7 m (15.3-15.5 ft)	2.07E-05	2.39E-08	2.39E-10	6.78E-05	7.84E-10	Slitcher
4.7 m (15.3-15.5 ft)	3.20E-05	3.70E-08	3.70E-10	1.05E-04	1.21E-09	Terzaghi
4.7 m (15.3-15.5 ft)	1.29E-04	1.49E-07	1.49E-09	4.23E-04	4.90E-09	Alyamani & Sen
4.7 m (15.3-15.5 ft)	9.73E-05	1.13E-07	1.13E-09	3.19E-04	3.70E-09	Hazen
4.7-4.8 m (15.5-15.6 ft)	5.08E-03	5.87E-06	5.87E-08	1.67E-02	1.93E-07	Kozeny-Carman
4.7-4.8 m (15.5-15.6 ft)	4.47E-03	5.17E-06	5.17E-08	1.47E-02	1.70E-07	Breyer
4.7-4.8 m (15.5-15.6 ft)	1.68E-03	1.95E-06	1.95E-08	5.52E-03	6.39E-08	Slitcher
4.7-4.8 m (15.5-15.6 ft)	2.94E-03	3.41E-06	3.41E-08	9.66E-03	1.12E-07	Terzaghi
4.7-4.8 m (15.5-15.6 ft)	3.17E-03	3.67E-06	3.67E-08	1.04E-02	1.21E-07	Alyamani & Sen
4.7-4.8 m (15.5-15.6 ft)	4.87E-03	5.64E-06	5.64E-08	1.60E-02	1.85E-07	Hazen

Table E.2. Average hydraulic conductivity for the aquifer and aquitard units in the Glasford deglacial unit.

	Average Hydraulic Conductivities (K)				
Unit	**m/day**	**cm/s**	**m/s**	**ft/day**	**ft/s**
Aquifer	4.27E+01	4.95E-02	4.95E-04	1.40E+02	1.62E-03
Aquitard	5.91E-01	6.84E-04	6.84E-06	1.94E+00	2.25E-05
Total	2.92E+01	3.38E-02	3.38E-04	9.58E+01	1.11E-03

Table E.3. Average hydraulic conductivities for unconsolidated glacial deposits (From Freeze and Cherry 1979).

	Range of Hydraulic Conductivities	
Unconsolidated Deposits	**cm/s**	**m/s**
Gravel	10^{-1} -10^{2}	10^{-3} -10^{0}
Clean sand	10^{-4} -1.0	10^{-6} -10^{-2}
Silty sand	10^{-5} -10^{-1}	10^{-7} -10^{-3}
Silt, loess	10^{-7} -10^{-3}	10^{-9} -10^{-5}
Glacial till	10^{-10} -10^{-4}	10^{-12} -10^{-6}
Unweathered marine clay	10^{-10} -10^{-7}	10^{-12}-10^{-9}

APPENDIX F

gOcad Cross-sections

The following are cross-sections constructed in gOcad extracted from the Glasford model. View direction from the north and east.

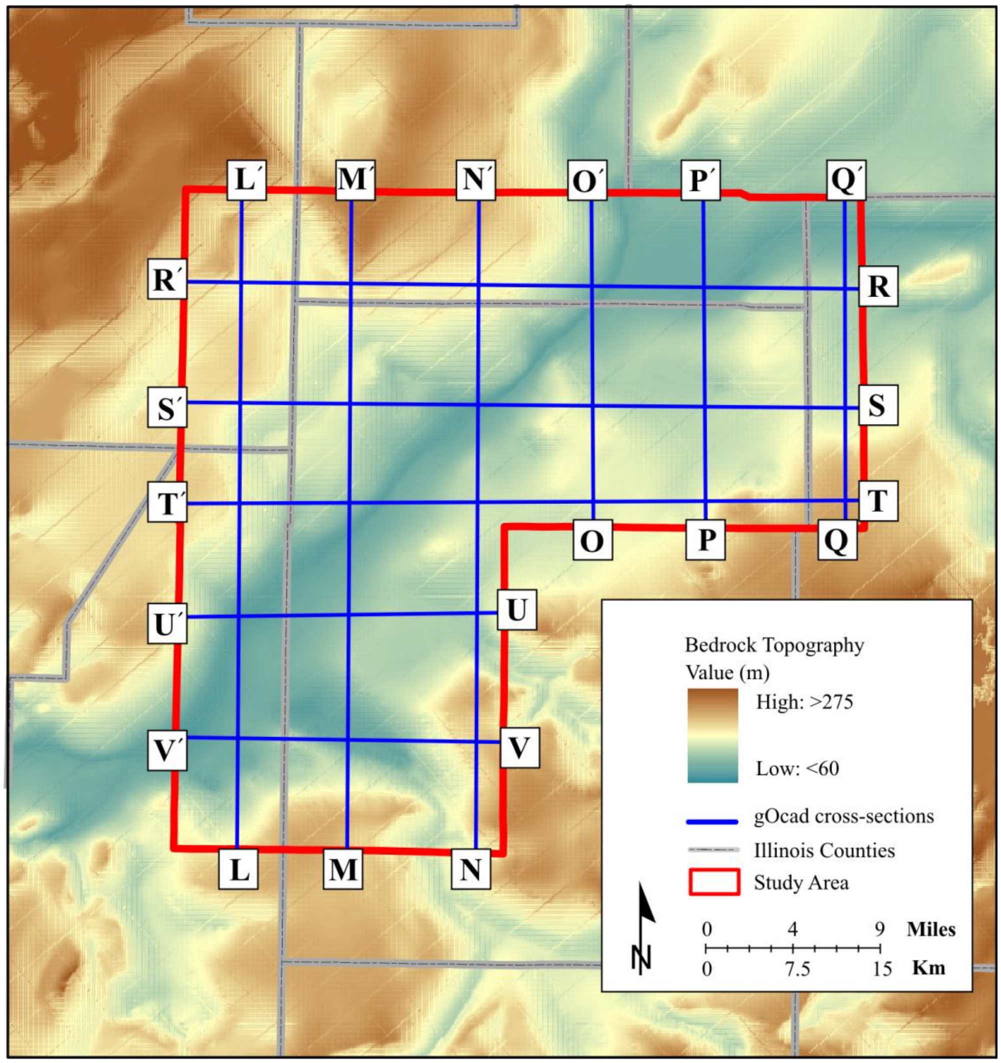


Figure F.1: Map of the cross-section location of the Glasford model (see Figure 3.6) shown in Chapter 3. The following cross-sections (shown in Figure F.2 to F.5) show detailed information from the Glasford model, which was incorporated into the ISGS model that show the sediments from land surface to bedrock.

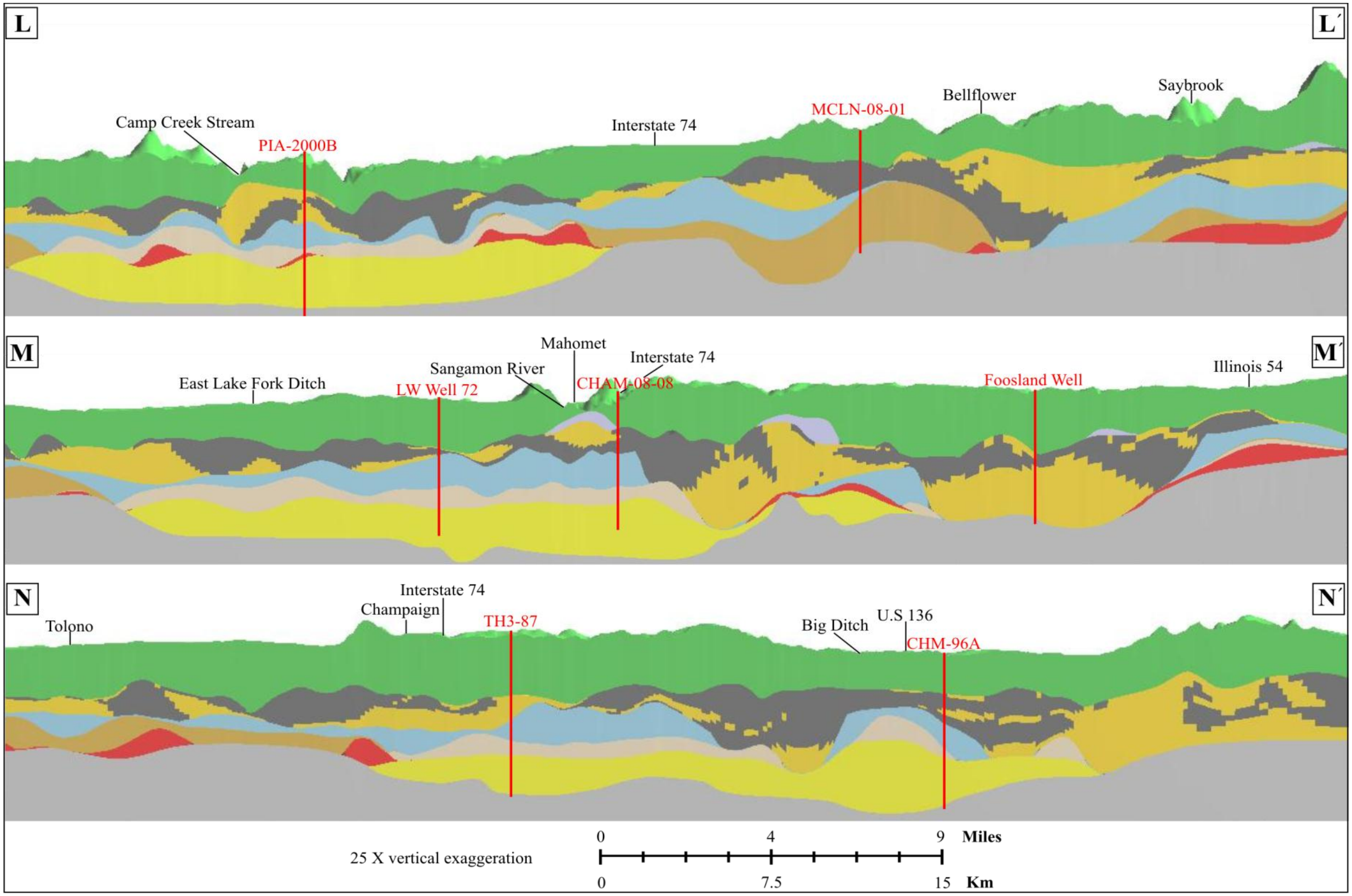


Figure F.2: Cross-sections L to N constructed in gOcad showing the valley emplaced into underling Illinoian and Pre-Illinoian sediments.

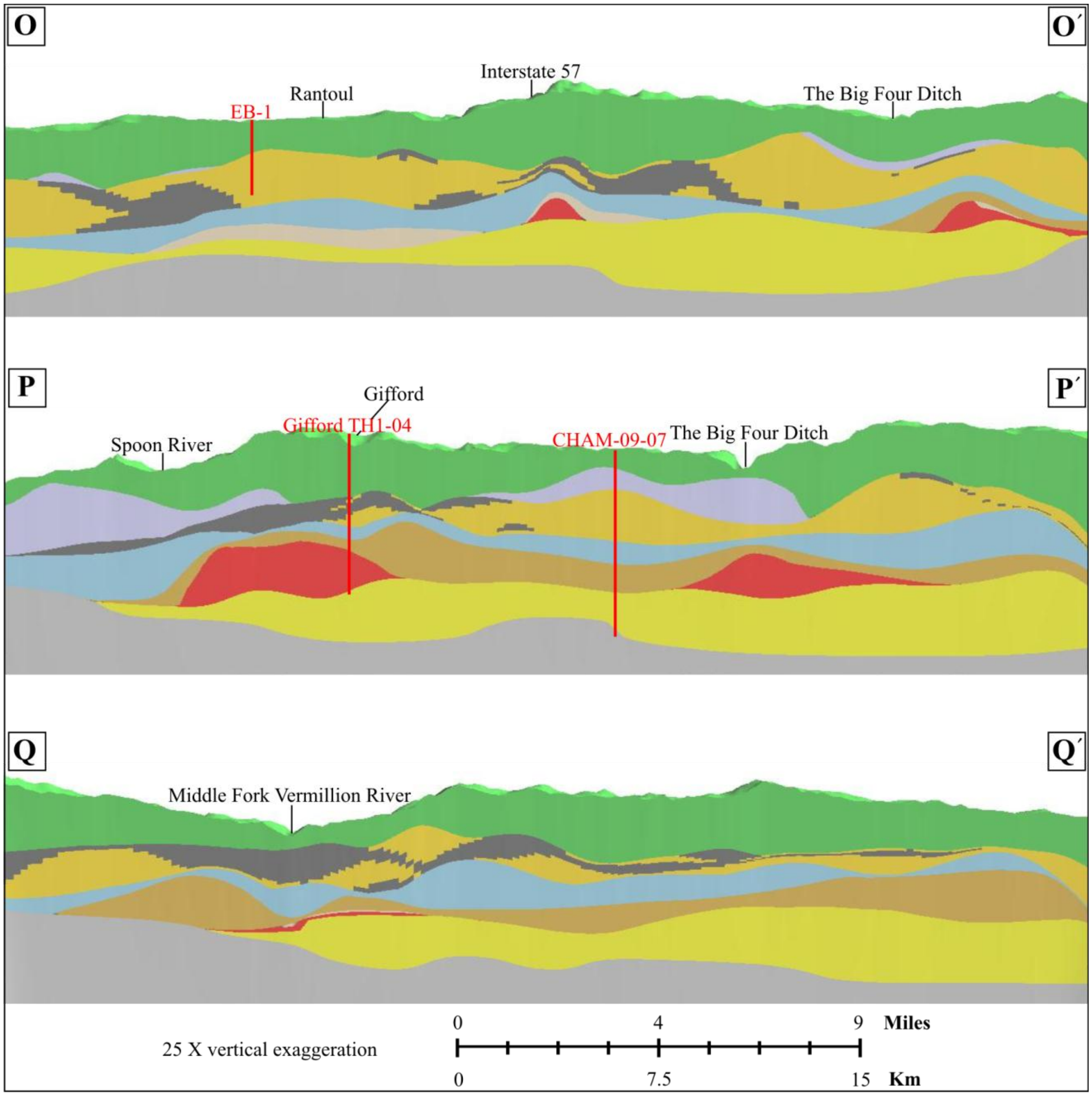


Figure F.3: Cross-sections O-Q constructed in gOcad showing the tabular unit overlying Illinoian and Pre-Illinoian sediments.

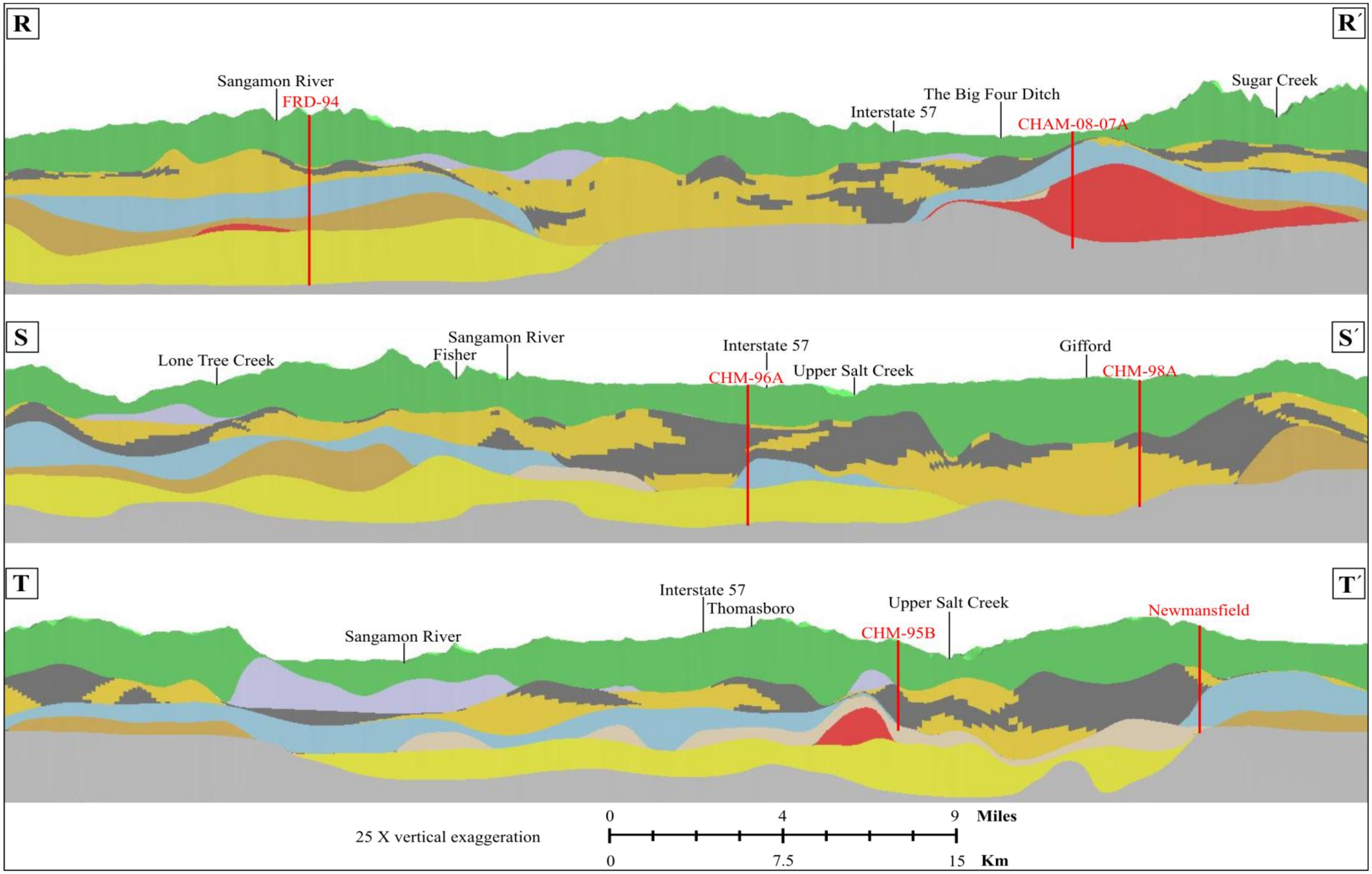


Figure F.4: Cross-section R to T constructed in gOcad showing assemblages of the Champaign valley and tabular units lying on older sediments and bedrock.

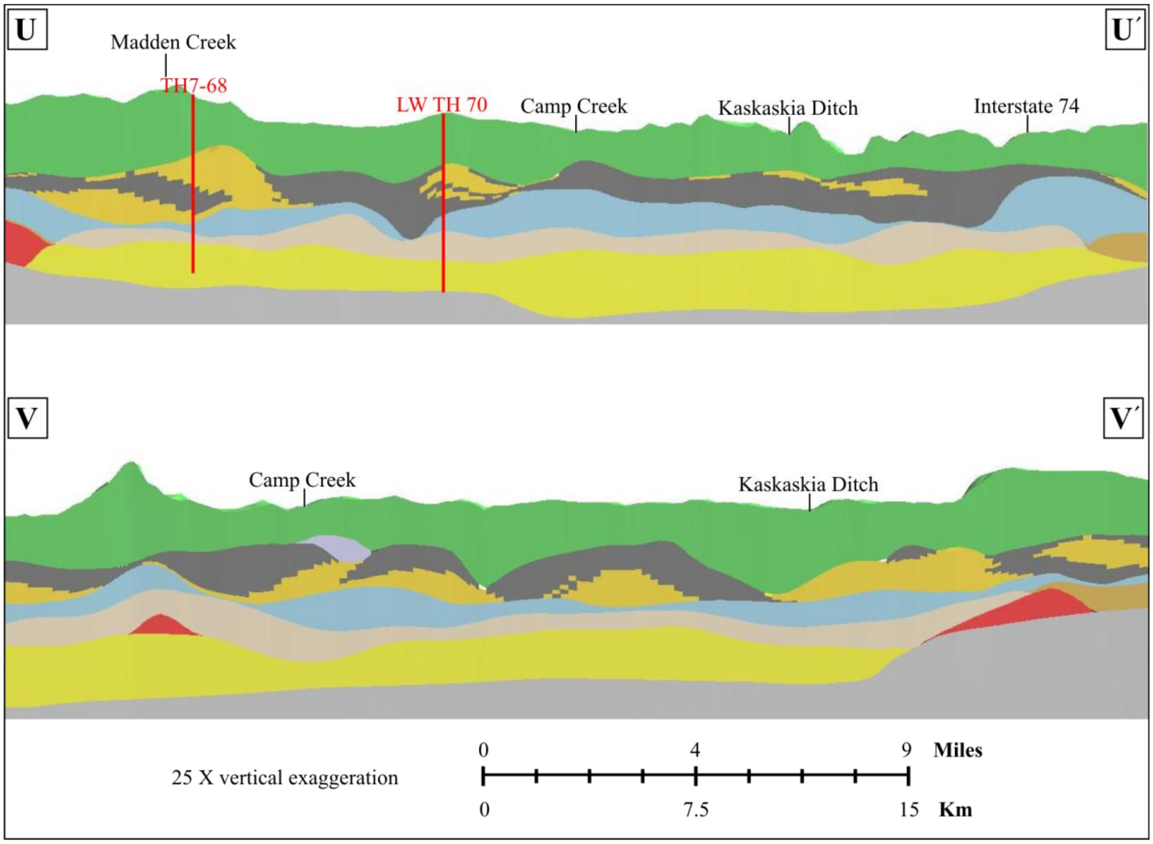


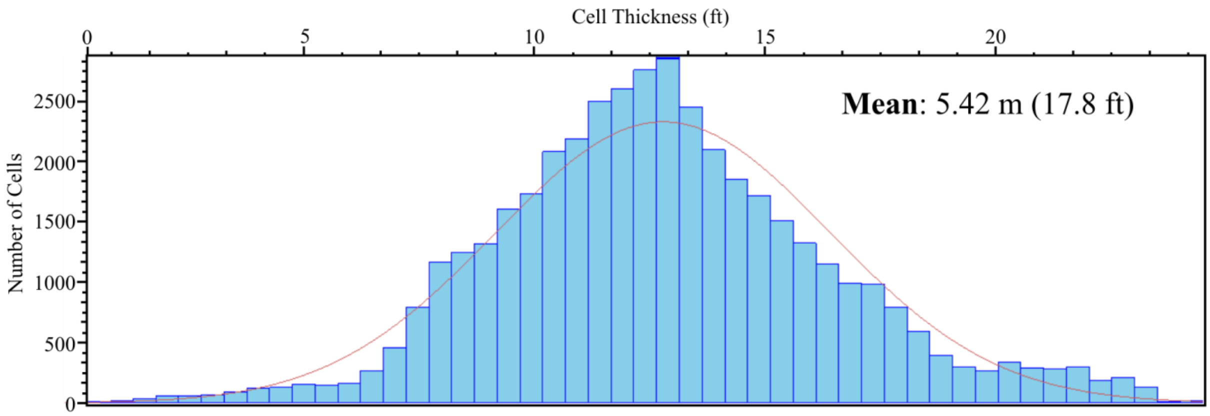
Figure F.5: Cross-sections U and V constructed in gOcad showing the tabular unit in the Glasford deglacial unit overlying older sediments.

APPENDIX G

Thicknesses of facies assemblages

Histograms showing thicknesses for facies assemblages V1-V3, and A-C for the Glasford model. The facies assemblage thicknesses were calculated in the gOcad software.

Facies Assemblage V1



Facies Assemblage V2

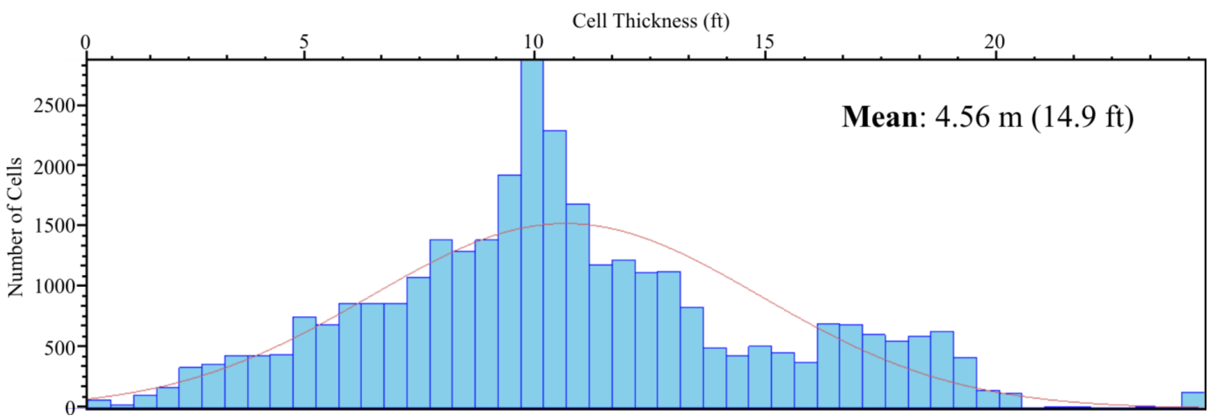
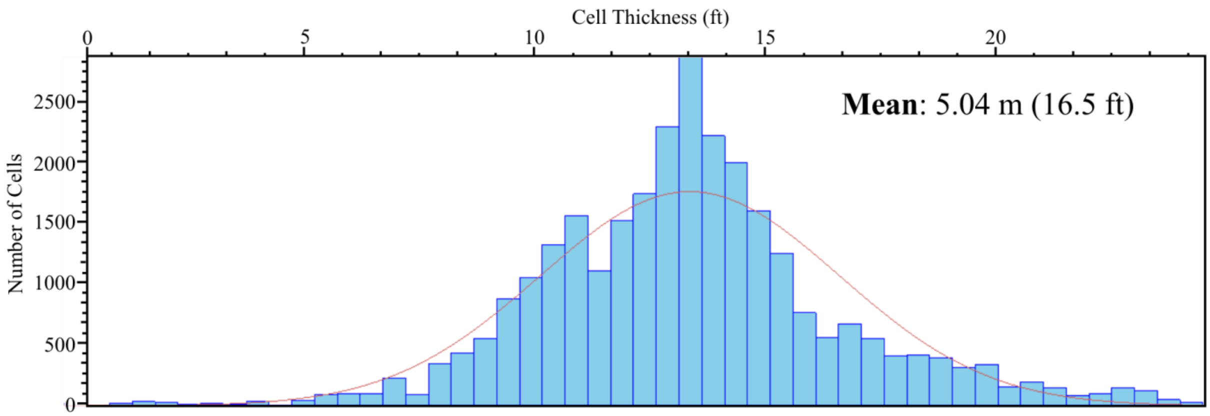
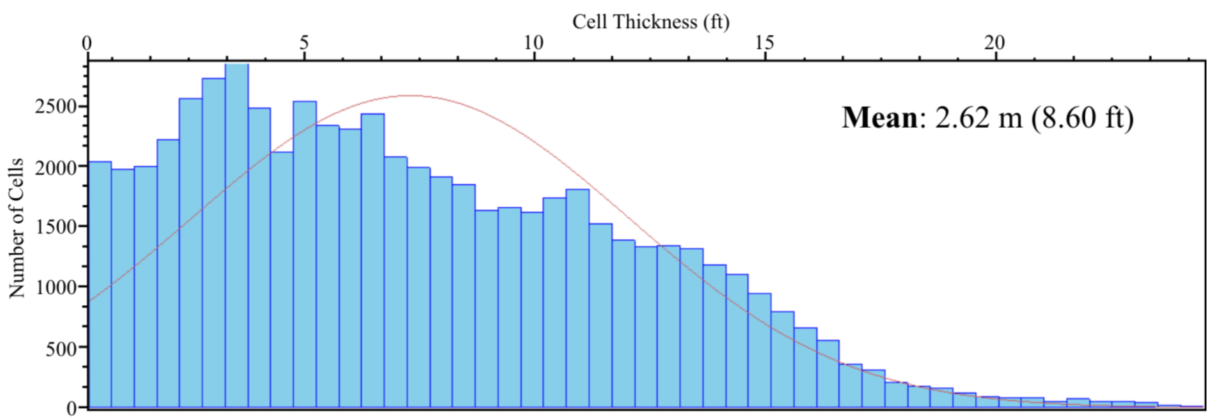


Figure G.1: Thicknesses of facies assemblages V1 and V2 taken from the Glasford model.

Facies Assemblage V3



Facies Assemblage A



Facies Assemblage Lower B

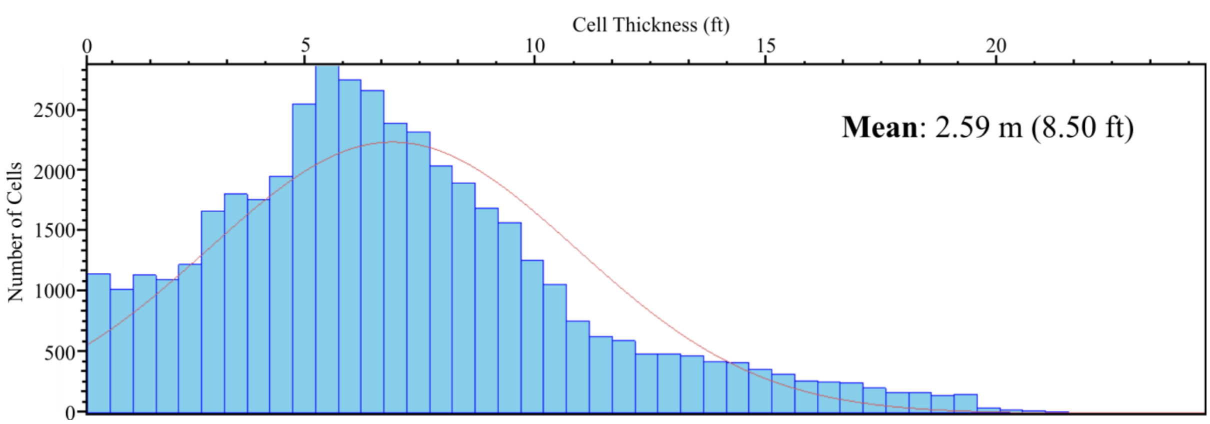
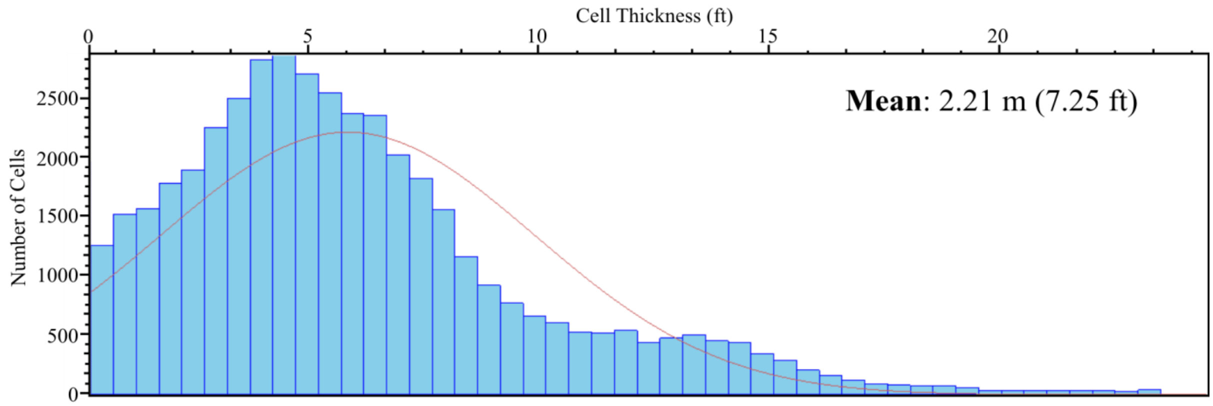
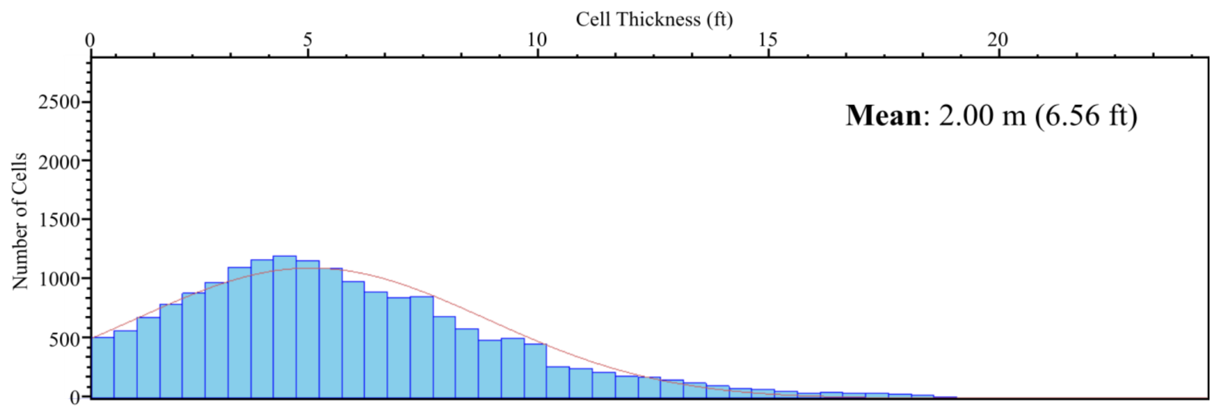


Figure G.2: Thicknesses of facies assemblages V3, A, and Lower B taken from the Glasford model.

Facies Assemblage Lower C



Facies Assemblage Upper B



Facies Assemblage Upper C

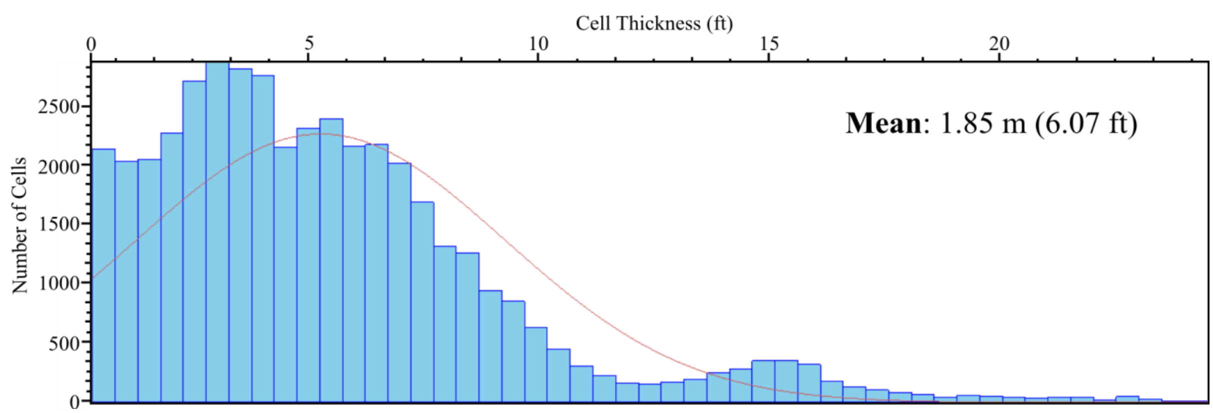


Figure G.3: Thicknesses of facies assemblages Lower C, and Upper B and C. The Lower C and Upper C as well as Lower B and Upper B are repeated in the stratigraphy of the Glasford deglacial unit.

APPENDIX H

Glossary

2-D: two-dimensional
3-D: three-dimensional
CPS: counts per second
DEM: digital elevation model
F: feldspar
f: fine
ft: feet
ft asl: elevation above sea level
GFM: Geological Framework Model
GIS: Geographic Information Systems
I: intermediate axis
IAWC: Illinois-American Water Company
ISGS: Illinois State Geological Survey
ISWS: Illinois State Water Survey
K: hydraulic conductivity
K: Potassium
km: kilometre
km^2: square kilometre
l/day: Litres per day
L: large size and/or large axis
lb: pound
LGM: last glacial maximum
LIS: Laurentide Ice Sheet
m.a.s.l: metres above sea level
m: medium
M: medium size and/or medium axis
m: metres
MBV: Mahomet Bedrock Valley
med: medium
mgd: millions of gallons per day
mi^2: square miles
MIS 6: Marine Isotope Stage 6
mm: millimetres
N/A : not available
Ohm-m: Ohm-metres
PLSS : public land survey system
Q: quartz
R: red
RF: rock fragments
RWSPC: Regional Water Supply Planning Committee
s: second
S: small size and/or small axis
SGRID: stratigraphic grid
Th: thorium
U: Uranium
U.S: United States
U.S.G.S.: United States Geological Survey
VL: vry large size
vry: vry
Y: yellow
YBP: years before present

APPENDIX I

Publications from the thesis work.

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Paper #196020

SEDIMENTOLOGY AND 3-D ARCHITECTURE OF SUBSURFACE FACIES OF THE ILLINOIAN DEGLACIATION IN EAST-CENTRAL ILLINOIS, UNITED STATES

ATKINSON, Lisa A.[1], ROSS, Martin A.[1], STUMPF, Andrew[2], and ISMAIL, Ahmed[2], (1) Earth and Environmental Sciences, University of Waterloo, 200 University Ave. West, Waterloo, ON N2L 3G1, Canada, lisaatkinson5@gmail.com, (2) Prairie Research Institute, Illinois State Geological Survey, 615 E. Peabody Dr, Champaign, IL 61820

Determining the character and distribution of deposits correlated to the deglacial phase of the Illinoian glaciation in central Illinois led to the identification of cut-and-fill deposits that are set into important aquitard materials that provide protection to shallow groundwater resources. However, the nature and mode of this incision, which emplaced coarse and/or fine-grained sediment, informally referred to as the Glasford deglacial unit, into the underlying Illinoian-age till are poorly understood. Consequently, sediment records from continuous cores and seismic facies interpretation of near-surface seismic surveys were used to elucidate these events. The Glasford deglacial unit is found in two distinct subsurface features: 1) a buried valley filled with four deglacial sediment assemblages (V1-V4), which breaches the regional aquitard of the Vandalia Member till; and 2) an overlying tabular body consisting of three facies assemblages (A-C). Specifically, the buried valley is filled by interstratified, massive, and laminated sand (V1 and V3), as well as by laminated to massive silt and clay, and diamicton (V2 and V4). The tabular body that overlies the valley-fill consists of a highly heterogeneous package of interstratified sand (B) and diamicton (A and C), and discontinuous layers of fine-grained material (A and C).

Relatively clean sand and gravel are considered the most productive aquifers in the Glasford deglacial unit. Facies assemblages B, V1, and V3 represent discontinuous aquifer materials that are potential groundwater sources for residents of central Illinois. Overall, groundwater flow in the deglacial unit is defined by the continuity and interconnectivity of permeable units, and to a much lesser extent controlled by deposits having a wide range of hydraulic conductivities that are arranged in a complex configuration within the unit. As a result, this study improves our understanding of these geologic events, and further evaluates sedimentary assemblages found at the margins of fluctuating glacial lobes. We are now able to determine in more detail the subsurface stratigraphic geometry and hydrostratigraphy of the Glasford deglacial unit, which may affect aquifer connectivity, water supply and quality.

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Paper #196111

3-D GEOLOGICAL MODELING OF SUBSURFACE FACIES ASSEMBLAGES CORRELATED TO THE ILLINOIAN DEGLACIATION IN EAST-CENTRAL ILLINOIS, UNITED STATES

ATKINSON, Lisa A.[1], ROSS, Martin A.[1], STUMPF, Andrew[2], and DEY, William S.[2], (1) Earth and Environmental Sciences, University of Waterloo, 200 University Ave. West, Waterloo, ON N2L 3G1, Canada, lisaatkinson5@gmail.com, (2) Prairie Research Institute, Illinois State Geological Survey, 615 E. Peabody Dr, Champaign, IL 61820

Three-dimensional geological modeling of complex and highly-heterogeneous deposits correlated to the deglacial phase of the Illinoian glaciation was undertaken as part of a regional groundwater study in east-central Illinois. These deposits, informally referred to as the Glasford deglacial unit, form discontinuous aquifers units that are utilized for self-supplied domestic groundwater sources. These supplies can be affected by increased water usage, climate change, and extraction of groundwater from deeper, higher capacity wells.

An important challenge in this study was to model these aquifer and aquitard geometries and their internal heterogeneity. In this part of Illinois, deposits of the Illinoian glaciation, including the Glasford deglacial unit are buried in the subsurface and are not widely exposed at the land surface. Furthermore, many sediment layers are discontinuous complicating the task of modeling aquifer connectivity. The methodology employed in this study relied on the analyses of continuous cores and near-surface geophysics, which provided key controls on unit geometry and facies changes both vertically and horizontally. Using the available data, a primary database was created for the Glasford deglacial unit for inclusion of data into the 3-D model. Construction of the 3-D model was completed using gOcad® (Paradigm™), a 3-D geomodelling software. Discrete triangulated surfaces were built by interpolating standardized data points representing the top of the Glasford deglacial unit as well as key internal layers. These surfaces were then used to build a SGRID object in gOcad, which is a 3-D cellular partition that allows for mapping internal properties of stratigraphic units.

Modeling the Glasford deglacial unit was particularly important to visualize the subsurface heterogeneities that affect fluid flow in the subsurface. In addition, the derivative data from the model will be beneficial to decision-makers and regulators in managing water resources. Yet, this study highlights the difficulty in representing the complexity of highly-variable deglacial sediment assemblages at a regional scale; however, attempts to model such heterogeneities within a stratigraphic unit is important as similar complex assemblages are prevalent throughout the glaciated regions of North America.

Sedimentology and 3-D architecture of subsurface facies of the Illinoian deglaciation in east-central Illinois, USA

Lisa Atkinson[1], Martin Ross[1], Andrew Stumpf [2,1], and Ahmed Ismail [2]
[1] *Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Ontario, Canada*
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ABSTRACT
The importance of understanding the character and distribution of deposits correlated to the Illinoian deglaciation in east-central Illinois lies in the potential for related events to have locally incised important aquitard materials that provide protection to shallow groundwater resources. However, the nature and mode of this incision into the Illinoian-age sediments, informally referred to as the Glasford deglacial unit, are poorly understood. Consequently, continuous cores and subsurface seismic methods were used to update the geological framework of east-central Illinois to provide understanding of the subsurface characteristics and preliminary geometry of deposits and related hydrostratigraphic units associated with the Illinoian deglaciation.

RÉSUMÉ
Il est important de comprendre la nature et la distribution des dépôts corrélés à la déglaciation illinoienne dans le centre-est de l'Illinois, car les événements qui y sont associés peuvent potentiellement avoir érodés des matériaux aquitards importants pour la protection des ressources d'eau souterraine peu profondes. Toutefois, la nature et le type d'érosion dans ces sédiments, l'unité informelle Glasford de la déglaciation, sont mal compris. Par conséquent, les forages continus et les méthodes sismiques ont été utilisés pour mettre à jour le cadre géologique et pour fournir une compréhension des caractéristiques de sous-surface et de la géométrie préliminaire des dépôts et unités hydrostratigraphiques associées à la déglaciation illinoienne.

1 INTRODUCTION

The Quaternary glaciations in Illinois deposited thick successions of sediments, producing unique landforms and deposits that record the advance and retreat of glacial lobes. There is a long legacy of Quaternary studies in Illinois dominated by traditional mapping and glacial stratigraphic studies (e.g., Leighton, 1960; Leighton & Brophy, 1961), which describe the genesis, extent, and mutual relationships of these widespread glacial deposits. However, the recent focus of research in Illinois has involved the mapping of glacial sediments in three-dimensions for environmental and groundwater applications (e.g., Dey et al., 2007; Stumpf et al., in press). The importance of mapping in three-dimensions for environmental applications was realized because of the heavy reliance on detailed subsurface information for agriculture, engineering and building purposes, aggregate exploration, and locating groundwater supplies. Specifically, studies of groundwater flow benefit greatly from this knowledge as the most productive aquifers in Illinois are composed of unconsolidated sand and gravel deposited during the Quaternary Period and these aquifers are a source of important water supplies. Consequently, as new techniques and processes have become more widely available for surface and subsurface geologic mapping (e.g., high resolution seismic and downhole geophysical tools, dating methods, digital mapping software and robust databases structures, etc.), new and important insights can be identified in previously mapped areas. As a result, geological frameworks are being updated, and the wealth of new data, especially subsurface data, allows additional areas of research such as sediment genesis, glacial processes, as well as the development of much needed quantitative models for groundwater flow.

In Illinois, previous investigations of glacial deposits focused primarily on mapping the extensively-preserved near-surface subglacial tills to establish the Quaternary stratigraphy of Illinois (e.g., Willman & Frye, 1970). These tills were used because their distinct and consistent character could be identified in the glacial sequence and correlations were subsequently made throughout the state. However, due to the state's low-relief, thick glacial drift, and paucity of outcrops, older glacial deposits of various origins in the subsurface were less frequently encountered and classified from limited exposures and split-spoon samples from drilling operations. More complex frameworks are now being considered as additional, more detailed subsurface data is acquired and consequently, some previously defined units are being re-examined and correlations are now interpreted with more caution.

An example of this re-examination is underway as part of a groundwater study in east-central Illinois, involving deposits classified to the Glasford Formation, which include successive subglacial tills that formed during the Illinoian as well as locally-thick deglacial deposits of Late Illinoian age. Three diamicton units previously classified to till members of the Glasford Formation include: locally the oldest Smithboro, Vandalia, and Radnor have been identified (Curry et al., 2011). New data collected for the study suggest that perhaps some of the diamictons are associated with the deglaciation following the regional advance of ice responsible for depositing the widespread Vandalia Member till. If true, the resulting deglaciation involved a variety of shifting ice-contact processes that dominated the landscape. For this study, this new conceptual model is used and the ice-contact sediments have been grouped into a Glasford deglacial unit.

Deposits of the Glasford deglacial unit are highly complex, laterally extensive, and contain a package of sediments that were previously mapped in east-central Illinois, as the subglacially-deposited Radnor Member till (e.g., Soller et al., 1999). This unit includes significant deposits of sand and gravel, commonly present between diamictons previously correlated to the Radnor and Vandalia members; however, on closer examination these sediments lack characteristics that would be diagnostic of subglacial deposition (e.g., high bulk density, abundant striated iron-shaped clasts arranged in a relatively consistent fabric), and they contain sorted sediments displaying features that could potentially be associated to a wide range of glacial processes. As a result, these diamictons are not necessarily subglacial tills and new analysis and interpretations are needed to update the geological framework of east-central Illinois, re-examine the Radnor Member classification, and include the Glasford deglacial unit in the stratigraphy.

Specific objectives of this paper include: 1) description of the sediment characteristics of the Glasford deglacial unit from continuous cores; 2) analysis of two-dimensional geophysical profiles, which provide key insights on unit geometry; 3) evaluation of the depositional history of the Illinoian deglaciation; and 4) discussion of the hydrogeological implications of these highly-complex and heterogeneous deglacial deposits. Consequently, this research will provide new insights on fluctuating margins of glacial lobes and the subsurface stratigraphic geometry and hydrostratigraphy of the Glasford deglacial unit.

2 STUDY AREA

The study area is located in east-central Illinois and covers parts of six counties that are mostly rural and contain many small communities and cities (Fig. 1). The study area was overridden by glacial ice of the Lake Michigan Lobe of the Laurentide Ice Sheet during the Late Wisconsinan glaciations, as well as by glaciers of the Illinoian and Pre-Illinoian stages. Sediments found at the land surface consist of Late Wisconsinan glacial tills and meltwater sediments. The older Illinoian landscape and associated sediments are buried in the subsurface and not widely exposed at the land surface. At the end of the Illinoian deglaciation, the ice sheet stagnated and melted in place (Stumpf et al., in press), depositing locally-thick deposits of ice-contact and ice-marginal sediments in the study area. It is apparent in subsurface records from east-central Illinois that these sediments forming the Glasford deglacial unit lie directly on the Illinoian-age Vandalia Member till and is overlain by sediments of the Late Wisconsinan. A paleosol associated to the last interglacial (i.e., Sangamonian time) is locally preserved separating the deposits of the Glasford Formation from the overlying Wisconsinan units (Hansel & McKay, 2010).

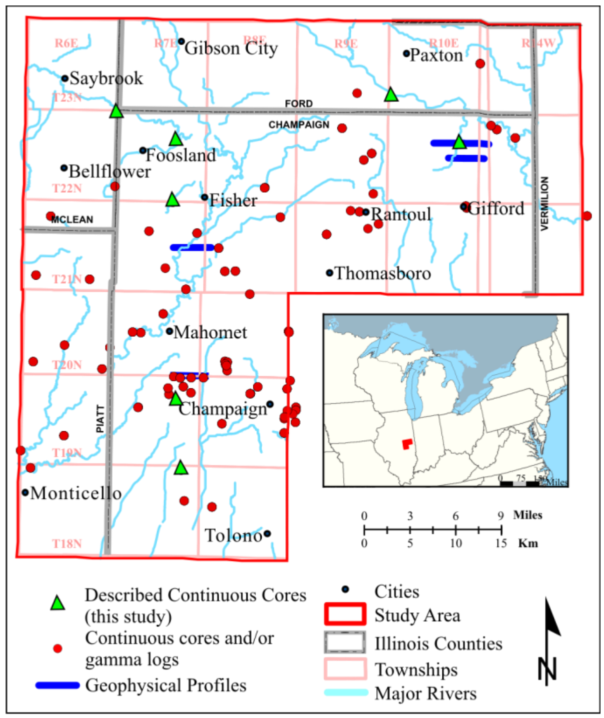

Figure 1. Map of the study area in east-central Illinois which encompasses a 2642 km^2 area of glaciated landscape.

3 METHODOLOGY

Because the Glasford deglacial unit is buried in the subsurface, the methodology to study these features has to rely on the analyses of continuous core and near-surface geophysics. The techniques entailed to characterize this unit include: 1) detailed facies descriptions from deglacial sediments in core; 2) grain size analyses of core subsamples; and 3) analysis of surface and downhole geophysical data.

The combined description of sediments in cores and documentation of the sediment properties using grain size analyses aided in the subdivision of distinct facies within the Glasford deglacial unit. Continuous cores for this study were acquired using the wireline mud-rotary drilling technique that utilized an inner barrel sampler for collecting the continuous core. A total of seven boreholes (totaling 612 m in length) were described for this study (Fig. 1). Each core averaged 87 m in total length (typically penetrating the bedrock), and 142 m of the total core contained sediments of the Glasford deglacial unit. After drilling the boreholes, downhole natural gamma logs were taken in counts per second (CPS), which provide a continuous quantitative measurement of the sediment properties in a well. Core recovery in the unit was generally very good allowing for detailed logging of core. Detailed descriptions of core include primary descriptive characteristics such as: sediment and clast lithology, clast roundness, sorting, morphology and form, sediment colour, and sedimentary structures. In each core, grain size samples were taken, which were selected to obtain quantitative textural information to compare with other more continuous qualitative descriptions (e.g., descriptive characteristics from cores) and to characterize the vertical changes in physical properties of the Glasford deglacial unit. In this study, fifty-five grain size samples were taken for grain size analysis from the cores. Grain size distributions were generated using two different methodologies: sieving and laser techniques. Sieving techniques used the Fritsch Analysette 3 Spartan shaker with five sieves (i.e., at intervals 0.6, 1, 2, 4, and 8 mm) while the Fritsch Analysette 22 MicroTec Plus was utilized for the laser analysis of the fraction that passed the 0.6 mm sieve.

Consistent with this documentation of the deglacial unit, the description of sediments using primarily geophysical approaches and to a lesser extent correlation of facies associations between cores provided an understanding of the three-dimensional geometry of the sediments classified to the Glasford deglacial unit. Subsurface geophysical methods were used to provide important continuous high-quality data of the subsurface. Seismic reflection data was collected using a P-wave land-streamer, a system designed at the Illinois State Geological Survey (Pugin et al., 2004b). The geophysical surveys were collected along approximately 8.8 km of roadway in the study area (Fig. 1). Facies seismic concepts were applied to the seismic lines by analyzing portions with differing aspects (e.g., amplitudes, frequencies and continuity of reflections) to identify large-scale trends within the Glasford deglacial unit. All seismic data collecting, processing, editing, and interpretations were performed at the Illinois State Geological Survey as a part of the Illinois-American Water contract report (cf. Stumpf et al., in press). Electrical Earth Resistivity data (EER) collected in the study area was also used for imaging the unconsolidated materials near the land surface. EER is particularly useful in identifying textural changes in glacial sediments, which create a wide range of resistances to flow of an electrical current. When measured, EER data can be used to locate resistive gravel and sand, and conductive deposits of silt and clay. In this study, the EER method was useful in determining the areal extent of sand and gravel bodies in the Glasford deglacial unit, and a rough estimate of the unit thickness could be calculated. Approximately 10 km of EER was collected in the study area along two east-west transects. All EER data processing, editing, and interpretations were made at the Illinois State Geological Survey by Tim Larson.

4 RESULTS AND INTERPRETATIONS

4.1 Facies Descriptions

Three main facies types were identified within the Glasford deglacial unit (Table 1). The facies include: 1) massive, matrix-supported diamicton; 2) interstratified sand and gravel; and 3) fine-grained massive and/or laminated sediment. Due to subaerial weathering of older glacial surfaces under interglacial conditions following the Illinoian glaciation the top sequence of these facies, locally can be constrained by the presence of a paleosol. The discontinuous presence of the paleosol in some areas provides adequate time constraints for the underlying facies to be Illinoian in age.

Table 1. Main facies types and characteristics

Facies Type	Characteristics	Total Thickness
Diamicton	Poorly-sorted, massive, predominantly silt loam in texture	~15-25 m
Sand and gravel	Poorly-sorted coarse sand with pebbles to massive or laminated fine sand	~20-40 m
Silt and clay	Massive or laminated clay or silt with minor amounts of sand	Thin; unit thickness <3 m

4.1.1 Diamicton facies

Poorly-sorted, massive, unconsolidated sediment containing a mixture of sand, silt, clay, gravel, and pebbles is referred to as diamicton (Dreimanis, 1989). The multiple diamictons identified in the cores contain at least 50% fine-grained material and predominantly have a silt loam texture. The diamictons are grayish-brown to dark-grayish brown (10YR 5/2) in colour. General characteristics of the diamicton units include: 1) an upper interval with no discernible internal structure; and 2) a lower interval of the sequence with lenses of sand and gravel with bounding contacts with surrounding material that vary in their character.

The diamictons were deposited by a variety of processes. They contain glacial sediments supplied by proximal ice lobes, which have been reworked and deposited primarily as debris-flows. In most cases, deposition by debris-flows processes destroys the original properties of the deposits, developing a multimodal and disoriented fabric. In addition, the diamicton display gradational contacts with surrounding material rather than distinct erosional contacts or major unconformities, which are also characteristics of debris-flow deposits. Lastly, the diamictons of the Glasford deglacial unit are less compact than diamicton of the underlying Vandalia Member till.

4.1.2 Sand and gravel facies

Coarse-grained sediments in the Glasford deglacial unit range from poorly-sorted sand with pebbles and cobbles to massive or laminated fine sand. Sand dominates the facies, with thin beds of gravel. The sand has a gravelly sand texture containing approximately 5-20% gravel with varying amounts of fine-grained material. Sand and gravel of this facies range from yellowish-brown, brown to gray (2.5Y 5/2) in colour. The sand and gravel is massive, horizontally bedded or laminated. In most of the cores, a well-developed internal stratification is uncommon; however, some plane and cross-laminated beds have been preserved. In some cores, a fining-upward trend can be identified in continuous core based on the logs of natural gamma radiation and grain size data.

Sand and gravel in the Glasford deglacial unit was deposited by flowing meltwater during the deglacial phase of the Illinoian glaciation. Variations in the mean grain size result from changing meltwater flow conditions and the overall sediment supply. The fining-upward successions common in the examined cores are due to waning flows and instances where cross-laminations and stratifications are present, migration and aggradation of bedforms generated sedimentary structures.

4.1.3 Silt and clay facies

These fine-grained materials are composed of a combination of silt and clay, and the texture depends on local depositional conditions and grain size of the material supplied. The silt and clay facies include massive or laminated clay or silt with minor amounts (approximately 10%) of sand and gravel. In the examined cores, the fine-grained facies has gradational contacts with the sand and gravel facies. This fine-grained material differs from the other materials in core, as the silt and clay are predominantly gray in colour (10YR 5/1). In some cases, sedimentary structures such as horizontal laminations are preserved; however, these materials are generally massive in nature. The silt and clay frequently compose thin layers or lenses of diamicton and sand and gravel.

The silt and clay facies represent materials that settled out from the water column, probably during the waning stages of flow of meltwater currents in the ice-contact environment. This facies has limited lateral extent and correlation with other boreholes is not often possible due to the heterogeneous nature of these ice-contact deposits.

4.2 Buried Valley

Variation in facies in cores and natural radiation gamma geophysical logs provide information about a buried Quaternary sediment valley system, which breaches the regional aquitard of the Vandalia Member till. The buried valley is a newly discovered feature in the study area (Fig. 2), and is such a large feature that it is regarded as one of the basic building blocks of the Glasford deglacial unit.

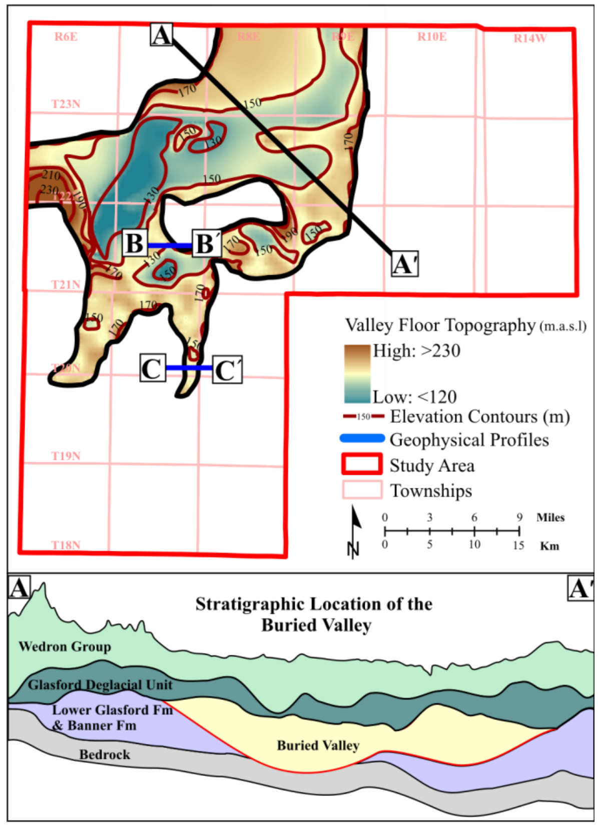

Figure 2. Cross-sections constructed across a buried valley in the study area and map showing the topography of the valley floor (Contour interval = 20 m). Cross section A-A' shows the geology across the buried valley in the described data sets.

The buried valley system extends across the study area and incises older glacial sediments. Its geometry is constrained by data from approximately 470 boreholes, including a limited number of continuous cores, logs of natural gamma radiation, descriptions of samples collected during the drilling of water wells, geological information recorded from the drilling of boreholes, and near-surface geophysical surveys. Valley-fill averages 70 m in thickness (Fig. 2). Much of the glacial material the valley incised includes: underlying till sheets (i.e., Vandalia Member till and Pre-Illinoian tills) and to a lesser extent underlying sand. There is no surface expression of the valley in the study area as it has been completely filled with sediments of the Glasford deglacial unit and younger Wisconsinan sediments. P-wave seismic reflection profiles show the

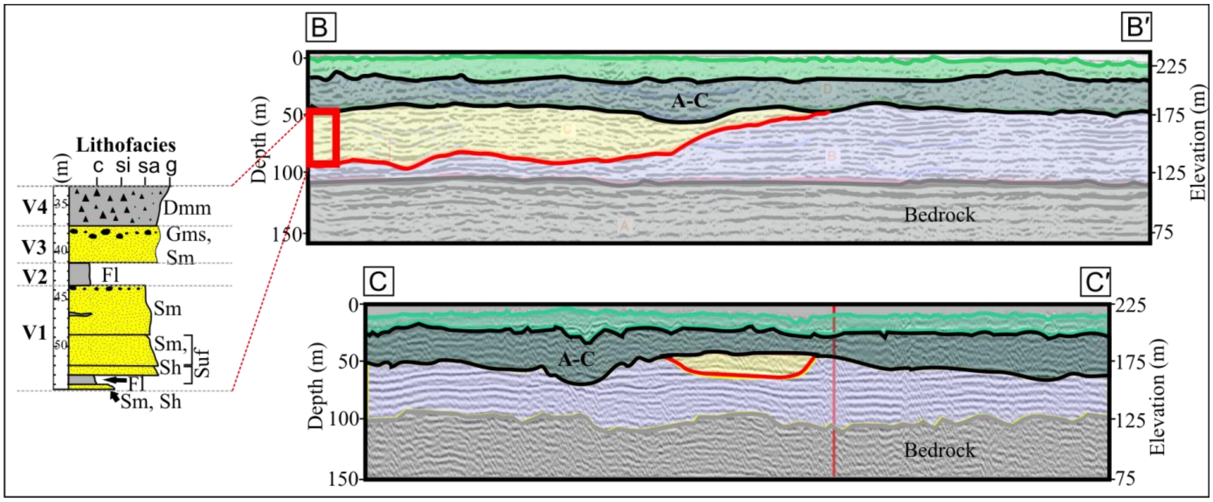

Figure 3. Interpreted seismic profiles of P-wave seismic reflection data (cf. Fig. 2 for location of profiles). Facies (A-C) are undifferentiated due to scale. Individual facies identified in continuous core from a borehole is provided as reference for valley-fill assemblages. The geophysical data shown in cross section B-B′ is from Pugin et al. (2004a), whereas that of cross-section C-C′ is from Stumpf et al. (in press). The vertical exaggeration for these two cross-sections is 10x. The lithofacies coding scheme used to describe the valley fill is from Eyles et al. (1983).

cross-sectional outline of the buried valley area along two transects (Fig. 3). Data collected from cores, downhole geophysical logs, and water wells in the valley show that the valley is filled with sand and gravel, diamicton, and silt and clay.

5 Facies Assemblages

Facies and facies associations have been grouped into distinct assemblages that are interpreted to be genetically-related. This grouping is useful to recognize and visualize assemblages of facies deposited during either the early deglaciation (i.e., buried valley and facies assemblages V1-V4) or late deglaciation (i.e., remaining deglacial sediments including facies assemblages A-C that extend across the study area and overlie the buried valley). Facies correlations were made using the described continuous cores (location provided in Fig. 1), material descriptions from water-wells, and geophysical data in the study area. Each facies assemblage identified provides information about a specific group of facies, its position with respect to adjacent units, and sediment characteristics. They are described informally below.

5.1 Early Deglaciation

Facies assemblages V1-V4 represent early deglaciation sediments. As shown in Fig. 3, lithofacies V1-V4 fill the valley that was incised into the lower Glasford and Banner formations. The valley-fill assemblages are buried by the remaining tabular deglacial facies assemblages (see section 5.2 below). The valley-fill sediments represent the oldest deposits correlated to the Glasford deglacial unit.

5.1.1 Facies Assemblages: V1 & V2

Facies assemblage V1 is a thick succession of vry fine to coarse sand, or gravelly sand. More specifically V1 mainly includes: 1) very fine-grained sand that is occasionally horizontally bedded; and 2) silt and clay-rich material with fine-laminations overlying the bottom of the buried valley (Fig. 3). Sediments overlying the fine-grained material consist of sand characterized by a clear fining-upward succession, which is identified in some continuous cores, as well as deposits of massive sand (Fig. 3). V1 is discontinuously covered with diamictons and fine-grained sediments that form facies assemblage V2. Because this unit is relatively thin and discontinuous the lateral continuity of V2 is limited between continuous cores. Overall, these assemblages are located primarily at the centre of the buried valley and their total thickness is approximately 15 m.

5.1.2 Facies Assemblages: V3 & V4

Facies assemblage V3 is composed mainly of fine to medium sand with concentrations of gravel more frequent near the top of V3. V4 contains diamictons with beds of very fine to fine sand. These assemblages are found to drape the underlying deposits on the valley sides, although they are occasionally more extensive laterally forming tabular bodies overlying V1 and V2. V3 and V4 generally coarsen-upwards (Fig. 3). No other sedimentary structures were observed in examined cores. However, this description is based on a single core and further drilling in the valley would be needed to fully document these assemblages. The combined thickness of V3 and V4 is estimated at approximately 8 m, but is based on limited data.

5.2 Late Deglaciation

As shown in Fig. 3, deposits of the early deglaciation are overlain by an extensive tabular body of sediments that also belong to the Glasford deglacial unit. These assemblages were thus formed later during deglaciation and are subdivided into three facies assemblages described below.

5.2.1 Facies Assemblage: A

The deglacial sediments that are situated over the buried valley consist of a basal, discontinuous highly-compacted diamicton. Facies assemblage A also includes discontinuous interbeds of sandy material; the interbeds are abundant near the bottom of the succession. Therefore, assemblage A has an overall fining-upward trend, ranging from a vry sandy diamicton to a silt loam diamicton. In some cores, this assemblage is found to compose the entire thickness of the Glasford deglacial unit. This facies assemblage has a variable thickness ranging between 4 and 8 m.

5.2.2 Facies Assemblages: B & C

Facies assemblage B consists of coarse and/or fine-grained sand with beds of gravel and pebbles. Facies assemblage C includes diamicton with minor beds of sand and gravel and/or silt and clay. These assemblages are discontinuous across the study area and overlie sediments (V1-V4) in the buried valley as well as facies assemblage A when present in the glacial sequence. In some areas, both assemblages (B or C) are located adjacent to till of the Vandalia Member (cross-section A-A′, Fig. 2). Assemblages B and C are separated by a gradational contact. In some areas, these assemblages are repeated as another cycle of sediments above. These assemblages represent the upper deposits of the Glasford deglacial unit. Locally, eluvial clay is preserved at the top of these assemblages, formed by secondary soil development during the Sangamon interglacial. Assemblages B and C constitute a significant portion of this deglacial unit ranging from approximately 5-35 m.

6 DEPOSITIONAL HISTORY

6.1 Valley-fill

The buried valley is filled by interstratified, massive, and laminated sand (V1 and V3), as well as by laminated to massive silt and clay, and diamicton (V2 and V4). The sand facies record events of an upper-flow regime when horizontal laminations are present (indicated by Sh in Fig. 3) or rapid sedimentation in water flow producing massive sands (e.g., Sm, Fig. 3). Waning flows created the laminated and/or massive silt and/or clay (e.g., Fl, Fig. 3) and possible debris-flow processes capped the top of the valley with diamictons. Based on the facies assemblages and the degree of heterogeneity, these valley-fill successions are linked to ice-contact or proximal glaciofluvial processes of varying energy and possible debris-flow mechanisms that deposited sediments during deglaciation. However, the exact nature of ice-contact (e.g., ice-marginal or subglacial) valley-fill origin remains uncertain.

6.2 Origin of Tabular Units

The tabular body that overlies the valley-fill and extends beyond the valley margins consists of a highly heterogeneous package of interstratified sand and diamicton, and discontinuous layers of fine-grained material. The coarse-grained sorted material is interpreted to be glaciofluvial in origin, and as discussed above, the diamicton is interpreted to be created from debris-flow processes. Debris-flow processes are the preferred interpretation for the diamicton due to the isotropic fabric and limited striations on clasts. As a result, this complex succession of highly heterogeneous meltwater deposits and diamicton is interpreted to record deglacial events in an ice-contact environment.

Previous interpretations of these deglacial sediments interpreted in this study include subglacial tills of the Radnor Member (Willman & Frye, 1970) that is correlative to diamicton units (i.e., facies assemblages A and C) with intercalated sand and gravel (i.e., facies assemblage B). A readvance of ice would be required to deposit the Radnor Member till, and thus the top horizons of underlying units would have erosional contacts or characteristics of glaciotectonites. Instead, contacts between facies assemblages B and C are somewhat gradational and the sediments do not exhibit evidence of deformation. Furthermore, the multiple cycles of the B and C assemblages is noted vertically in cores, rather than upward thickening of diamicton units associated with typical ice advance sequences. Therefore, there is no clear evidence for distinguishing a separate ice advance in the study area; however, there could have been areas of local readvance of glacial sublobes at the margins of the ice sheet (Grimley & Philips, 2011; McKay et al., 2008) that deposited the Radnor Member till. Therefore, the most likely origin for the highly heterogeneous sediment assemblages is through ice-contact or ice-proximal processes. Whether these processes are associated with ice readvance or retreat has yet to be established.

6.3 Formation of the Buried Valley

The buried valley that underlies a large portion of the study area (Fig. 2) is thought to be associated with deposition of the Glasford deglacial unit, and discerned by geological information from cores and geophysical surveys. The age of the valley is well constrained to the latter part of the Illinoian stage (Marine Isotope Stage 6) because the valley is incised into till of the Vandalia Member and older Illinoian and Pre-Illinoian sediment and the valley fill is overlain by deglacial deposits containing a paleosol (Sangamon Geosol) in its upper part (Stumpf et al., in press).

Similar buried valleys have been encountered in glaciated North America and thought to have formed by varying processes such that comparisons can be made.

Table 2 lists the key features and characteristics of the buried valley in this study as well as selected glacial valley systems from southern Canada and the north-eastern United States. Information about the valley systems are compared to contrast different morphologies, in-fill processes, and interpreted formation.

For this study, two possible origins for the buried valley that developed during the Illinoian deglaciation include: 1) erosion by subaerial glaciofluvial processes in a proglacial environment with the retreat of the ice sheet; or 2) a subglacial tunnel valley system formed at the margin of the ice sheet. Subaerial glaciofluvial processes taking place at or beyond the ice-margin may have caused significant erosion of the substratum resulting in a relatively large valley system. Subglacial processes may have also been responsible for the formation of the valley system. Subglacial meltwater, under glaciohydrostatic pressure and flowing on a soft and erosional bed, may cause the erosion and evacuation of sediments forming Nye channels or tunnel valleys (Cofaigh, 1996). Different mechanisms have been proposed for their formation and they broadly fall into two categories: steady-state and relatively slow mode (e.g., Cofaigh, 1996) or a catastrophic and vry rapid mode (e.g., Hooke & Jennings, 2006). Regardless of the exact mode of formation, these valleys are distinct from subaerial glaciofluvial valleys as they are characterized by undulating longitudinal long profiles with isolated areas of overdeepening. In the subglacial environment ice as well as meltwater under glaciohydrostatic pressure can erode deeply in the substrate. Furthermore, confining pressures can cause meltwater to flow up slope. A closer look at the topography on the valley floor (Fig. 2) suggests that the valley is indeed characterized by an undulating valley profile. However, the valley floor topography shown in Fig. 2 should be regarded as preliminary, constructed primarily from geologic logs recorded during drilling of water wells and seismic data from limited geophysical surveys. Thus, uncertainty remains on the exact dimensions of the valley and topography of the valley floor because of limited data and variability in the accuracy of information. Yet, in the available data and one particular continuous core (Fig. 3) the data is consistent with the overdeepenings of the valley under subglacial conditions. However, sedimentation in the valley may be due to several processes in the proglacial environment, and thus the events that deposited the valley-fill may not be related to the ones that formed the valley.

Table 2. Buried valley successions in adjacent areas

Region	Morphology	In-fill	Type
East-central Illinois (This study)	High width to depth ratio. Average depth approx. 100 m and width 7.4 km. Total extent unknown.	Basal sand and gravel, pitted with diamictons and fines, sand, gravel, and/or diamicton draping valley sides.	Subaerial glacio-fluvial or subglacial tunnel valley.
Prairie region of Canada & parts of USA (Sharpe, 2009)	Low width to depth ratio. Several to several tens of meters in average depth.	Sand and gravel at the base of the valley with mostly diamicton with some sand beds in-filling remaining portions of the valley.	Buried glaciofluvial valleys.
New York Finger Lakes (Petruccionne et al., 1996)	Broad and shallow channels with undulatory bed-long profile. Max width of 6 km over 25 km.	Basal coarse-grained channel-fill. Further in-fill of fine-grained material with the presence of post-glacial lakes.	Subglacial meltwater channelized region.

7 HYDROGEOLOGY IMPLICATIONS

Relatively coarse-grained sand and gravel are considered the most productive aquifers in the Glasford deglacial unit. Facies assemblages B, V1, and V3 represent discontinuous aquifer materials that are potential groundwater sources for residents of east-central Illinois. Currently, water-bearing units in the Glasford Formation are used primarily for self-supplied residential water supplies; however, connections with underlying aquifers (i.e., aquifers in a bedrock valley present in the study area) may provide increased water-bearing capacities for deep wells that supply municipalities in the study area. Overall, groundwater flow in the Glasford deglacial unit is defined by the continuity and interconnectivity of permeable units, and to a much lesser extent controlled by hydraulic conductivities (cf. Martin & Frind, 1998 references therein). As a result, aquifers in the Glasford deglacial unit are a viable water source when lateral or vertical interconnections exist with adjacent aquifer materials, although they may only be useful for local low-capacity water supplies.

The extensive tabular body of deglacial sediments is highly heterogeneous in nature and contains layers of fine-grained sediments and diamicton considered as aquitards. The stratigraphy in the Glasford deglacial unit includes a variety of sediments having a wide-range of hydraulic conductivities that are arranged in a complex configuration. Consequently, due to the discontinuous nature of the fine-grained materials and complexities that exist (e.g., beds of sand and gravel) these materials may not be the most effective confining layers for inhibiting the downward mitigation of contaminants into deeper groundwater. the buried valley system that incised into a significant regional aquitard (i.e., the Vandalia Member till) further advancing the model of groundwater flow. Also, this study provides insight on the implications this incision and presence of the Glasford deglacial unit have on aquifer connectivity, water supply and quality.

8 CONCLUSIONS

Continuous cores and near-surface seismic methods were used to improve the description and understanding of the Illinoian deglacial record in east-central Illinois. Facies in the Glasford deglacial unit include: 1) massive, matrix-supported diamicton; 2) interstratified sand and gravel; and 3) fine-grained massive or laminated sediment. Grouping of genetically-related facies into facies assemblages (i.e., units A-C and V1-V4) was critical in developing an understanding of the subsurface geometry and lateral extent of the deglacial deposits. An updated geological framework also aided in the identification of a large buried valley associated with the Illinoian deglaciation on the basis of stratigraphic relationships with paleosols and other marker beds. The identified valley breaches a regional aquitard (i.e., Vandalia Member till) and valley-fill consisting of Glasford deglacial sediments include: significant deposits of sand and gravel, coarse-grained sediments draping the valley sides, discontinuous diamicton units, and fine-grained sediment layers. The origin of the valley and its in-fill history appear to be complex and uncertainty remains on the relation of events. However, preliminary interpretations suggest that a subglacial tunnel valley with progressive valley-fill situated within a variety of glacial depositional settings is the most likely origin.

A buried valley has been identified in the study area, and the overlying tabular deglacial facies are now better defined. Further drilling and geophysical surveys should be directed towards better characterizing the Glasford deglacial unit and the geological complexities that exist in the buried valley and overlying deposits, which are a source of local water resources. However, it has become clear that complexities that exist in these ice-contact and/or proximal assemblages prove difficult to reliably identify water supplies and maintain their protection and management. As a result, improved delineation of the extent of the buried valley and additional characterization of the tabular deglacial facies will aid in the more complete understanding of the Glasford deglacial unit in Illinois.

The development of an updated geological framework for the study area allows for the introduction of

ACKNOWLEDGEMENTS

This project was funded by the Illinois-American Water Company and the State of Illinois. Additional support to L. Atkinson and M. Ross was provided by the Canadian Water Network and the Canada Foundation for Innovation.

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