Glacial Stratigraphy of the Ridge River Area, Northern Ontario: Refining Wisconsinan Glacial History and Evidence for Laurentide Ice Streaming

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Graduate Program in Geology

A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science

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by

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Abstract

Detailed field studies of Quaternary sediments were undertaken during the summer of 2012 in the remote Ridge River area of the Hudson Bay Lowland. Grain size, carbonate content, stone lithologic analyses and stratigraphy of 31 sites were compiled, and revealed two main till units likely deposited by the advance and retreat of the Laurentide Ice Sheet. Based on grain size, carbonate, and lithologic data the two tills could not be distinguished and the abundance of distantly transported stones suggests rapid flux of glacial debris from Quebec over the Hudson Platform to the study area. Evidence from stone fabrics, striae, and glaciotectonic structures in the tills indicate that a large component of ductile deformation occurred. Both lodgement and deformation facies appear in the tills, suggesting that multiple rheologic states were superimposed during till deposition. The results also indicate that ice streaming was plausible through the Ridge River area as subglacial conditions were favourable to rapid ice flow.

Keywords

Glacial, Geology, Quaternary, Stratigraphy, Glaciation, Ice Streaming, Till, Hudson Bay Lowland, Ridge River, Laurentide Ice Sheet
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Table of Contents

Abstract.........................................................................................................................ii

Acknowledgements......................................................................................................iii

Table of Contents........................................................................................................iv

List of Tables................................................................................................................vi

List of Figures...............................................................................................................vii

List of Appendices.......................................................................................................viii

Chapter 1......................................................................................................................1

1 Introduction...............................................................................................................1

1.1 Rationale...............................................................................................................1

1.2 Setting & Study Area.............................................................................................2

1.3 Local Bedrock Geology.........................................................................................3

1.4 Regional Quaternary Geology/History.................................................................5

1.5 Previous Work.......................................................................................................8

Chapter 2.....................................................................................................................11

2 Field Studies.............................................................................................................11

2.1 Access to Area.....................................................................................................11

2.2 Sample Locations................................................................................................13

2.3 Sampling Techniques..........................................................................................14

2.4 Till Fabrics, Structural Data & Striae..................................................................15

2.5 Stratigraphy..........................................................................................................17

Chapter 3.....................................................................................................................27

3 Analytical Methods & Data Presentation...............................................................27

3.1 Particle Size Distribution....................................................................................27
List of Tables

Table 3.1 – Particle Size Distribution Summary .........................................................29
Table 3.2 – Carbonate Analysis Summary ..................................................................32
Table 3.3 – Pebble Roundness Summary ..................................................................36
List of Figures

Figure 1.1 – Location of the Ridge River Area.................................................................2
Figure 1.2 – Location of the Moose River Basin.............................................................3
Figure 1.3 – Bedrock Geology Map of Northern Ontario..............................................5
Figure 1.4 – Major Ice-Flow Directions for Hudson Bay Lowland Tills.........................7
Figure 1.5 – Geologic Domains of the Hudson Bay Region.........................................8
Figure 2.1 – Map of the Ridge River Area with Sample Location.................................12
Figure 2.2 – Example of SPOT Imagery.........................................................................13
Figure 2.3 – Photo of Work at Site #23........................................................................14
Figure 2.4 – A:B axes of pebble....................................................................................16
Figure 2.5 – Summary of Stratigraphy..........................................................................18
Figure 2.6 – Photo of Organic Rich Beds at Site #7.......................................................19
Figure 2.7 – Stratigraphy of Site #7.............................................................................20
Figure 2.8 – Photo of Branch from Site #7.....................................................................21
Figure 2.9 – Photo of Site #17....................................................................................23
Figure 2.10 – Photo of Site #31...................................................................................24
Figure 2.11 – Photo of Post-Glacial Sediments in Site #17.............................................25
Figure 3.1 – Ternary Plot of Sand, Silt, and Clay Proportions.........................................29
Figure 3.2 – Chittick Apparatus..................................................................................30
Figure 3.3 – Total Carbonates vs. Calcite/Dolomite Plot.............................................32
Figure 3.4 – Pebble Classification Groups..................................................................33
Figure 3.5 – Histogram of Average Pebble Lithologies.................................................34
Figure 4.1 – Schmidt Plot of Site #22L ......................................................................37
Figure 4.2 – Rheologic Superposition Model...............................................................38
Figure 4.3 – Photo of Omar........................................................................................39
Figure 4.4 – Illustration of Boothia and Dubawnt Type Dispersal..................................40
Figure 4.5 – Location of Proposed Ice Stream............................................................41
Figure 4.6 – Textural Comparison of Tills..................................................................42
Figure 4.7 – Digital Surface Model of the Ridge River Area......................................43
Figure 4.8 – S₁ vs S₃ Eigenvalue Plot...........................................................................45
# List of Appendices

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Particle Size Distribution</td>
<td>52</td>
</tr>
<tr>
<td>B</td>
<td>Carbonate Analysis</td>
<td>53</td>
</tr>
<tr>
<td>C</td>
<td>Pebble Counts</td>
<td>54</td>
</tr>
<tr>
<td>D</td>
<td>Pebble Roundness</td>
<td>55</td>
</tr>
<tr>
<td>E</td>
<td>Fence Diagrams</td>
<td>56</td>
</tr>
<tr>
<td>F</td>
<td>Stratigraphic Sections</td>
<td>59</td>
</tr>
<tr>
<td>G</td>
<td>Equal Area (Schmidt) Projections</td>
<td>65</td>
</tr>
</tbody>
</table>
Chapter 1

1 Introduction

1.1 Rationale

A comprehensive study of the Quaternary sediments in the Ridge River area (RRA) of the Hudson Bay Lowland provides valuable insight into the glacial history of a region which until now has been studied only in reconnaissance. While the evolution of the Laurentide Ice Sheet (LIS) is generally understood on a regional scale, the poorly constrained chronology and the fragmentary nature of the stratigraphic record have yielded ambiguous results. Thus, the behaviour and configuration of the LIS in the RRA is still only generally known. The location of the RRA near the geographic centre of the former LIS is particularly important as sediments record ice sheet events that affected areas farther down ice.

Large riverbanks cut into this largely flat-lying area offer opportunities to study the underlying stratigraphy. A detailed study of the stratigraphic record along with compositional and structural analyses of the till units in the RRA may refine the chronology and the local ice sheet configuration during the last glaciation. These efforts may yield new stratigraphic data that help to improve our understanding of the events associated with the LIS. Ice flow directions and till sheet properties also may be useful for drift exploration of economically valuable minerals and may promote future exploration in this sparsely studied region.
1.2 Setting and Study Area

This thesis completes a detailed stratigraphic study of the RRA covering some 6000 km² in the Hudson Bay Lowland. The RRA lies approximately 85 km north of the town of Hearst, Ontario in the Cochrane District (Fig. 1.1). Access to the RRA is only feasible via helicopter due to the large distances and the lack of roads (see Chapter 2.1).

Fieldwork was conducted during the summer of 2012 with Dr. Peter Barnett of the Ontario Geological Survey as part of their Far North mapping project. Surficial and bedrock mapping in this remote region is largely hindered by dense forest cover, swampy terrain, limited exposures, and lack of accessibility. In fact, very little bedrock is exposed as the study area is largely mantled by thick glacial sediments.

Figure 1.1 – Location of the RRA and Hearst, Ontario (Modified from Ministry of Natural Resources, 2013).
The RRA is centred on the Ridge River which runs roughly east-west and joins with the much larger Kenogami River at its western end. The majority of sample sites are located along the Ridge, whereas some samples were taken along Kenogami, Squirrel, and Pivabiska rivers. The RRA is north of the Laurentian (north-south) continental divide, lies completely within the Hudson Bay drainage basin, and is located at the western end of the Moose River Basin (Fig. 1.2). Both the Ridge and Squirrel rivers drain west into the Kenogami and north until it converges with the Albany River before flowing into Hudson Bay. The Pivabiska drains east into the Missinaibi River before entering Hudson Bay via the Moose River. The topography of the RRA is mainly flat with topographic highs toward the southern part which is coincident with the change from Paleozoic carbonates to Shield rocks. The flat topography hinders drainage and is largely responsible for the proliferation of swampy terrain throughout the region. Drainage patterns are predominantly controlled by drift morphology as bedrock structures are rare in the RRA.

1.3 Local Bedrock Geology

The RRA lies along the border of two major geologic domains; the Hudson Platform and the Canadian Shield. The boundary between the two domains extends roughly east-west immediately south of the RRA. A prominent protrusion of Canadian Shield bedrock occupies a large portion of the study area and comprises mainly supracrustal Neo- to Mesoarchean (2.5-3.4 Ga) paragneisses and other metasedimentary rocks (Ontario Geological Survey, 1991). In many areas these have been folded and intruded by Archean mafic to felsic metavolcanic rocks (Bennett et
Mafic to intermediate metavolcanic rocks of similar age (2.5-3.4 Ga) are found south of the Pivabiska River. Carbonatitic intrusions of unknown age are also found near the tip of this protrusion. Similar carbonatites in the region have been found to contain iron and copper (Bennett et al., 1967).

The mineral potential of Moose River Basin has been explored on numerous occasions over the past century. One of the more prominent studies, Operation Kapuskasing, was undertaken by the Ontario Department of Mines during the 1960s, which revealed previously undiscovered occurrences of base metals, as well as large reserves of non-metallic minerals such as lignite and kaolin. However, the extent and economic potential of most of these deposits are still unclear even after nearly a century of exploration.

The majority of bedrock in the RRA comprises Paleozoic sedimentary rocks of the Hudson Platform, a major geologic domain covering approximately 1.5 million km² (Sanford & Grant, 1990). Middle Devonian limestone, dolostone and shale unconformably overlie Precambrian Canadian Shield rocks in the RRA. Upper Silurian to Lower Devonian shales and dolostones of the Kenogami River Formation are found along the far western part of the RRA starting near the confluence of the Ridge and Kenogami Rivers. Progressively younger rocks of the Hudson Platform are found eastward toward the centre of the basin crossing the Stooping River, Kwataboahegan, Moose River, and Williams Island Formations respectively (Fig. 1.3). Limestone is the predominant bedrock in the RRA although the Moose River Formation also contains noticeable amounts of shale and evaporites (Sanford & Grant, 1990). Mesozoic shale of the Mattagami Formation occupies the eastern part of the RRA and is one of the main units underlying the Moose River Basin.

Bedrock lithology is often an important factor in inferring the amount of basal friction that glacial ice exerted while overriding bedrock. This is particularly significant to the RRA because it lies along the border of two vastly different and contrasting types of bedrock. The friction between ice and bedrock can influence movement of an ice sheet by affecting the speed and direction of ice flow (e.g. Benn and Evans, 2010). In fact, low basal friction plays a key role in initiating rapid ice flow and ice streaming (see Chapter 4.2).
1.4 Regional Quaternary Geology/History

An understanding of the flow patterns of the LIS is fundamental not only for interpreting the drift deposits in the RRA, but also for understanding the glacial history and landscape development of central North America during the last glaciation. The growth, decay, and configuration of the LIS also influenced global climate and sea levels during the Pleistocene. Ice-flow in the Hudson Bay Lowland is of particular interest because the region lies near the centre of the former LIS. Consequently, drift deposits in this region should reflect the development of the LIS during various stages of growth and deglaciation (Patterson, 1998). Determining accurate ice-flow pathways during glacial dispersal of economic minerals is also essential for successful drift prospecting of mineral deposits. Ice movement may be reconstructed from stone and bedrock striae, till fabrics and provenance of lithologically distinct erratics.
Detailed studies of river banks in the Hudson Bay lowland have revealed a complex sequence of glacial and non-glacial sediments spanning multiple glaciations. The stratigraphic record exposed in the RRA largely consists of two till units (designated as “upper” and “lower”) alternating with a series of sand and silt beds that together represent the oscillation and eventual demise of the LIS during the last glaciation (referred to as the Wisconsin glaciation). Although a general sequence of glacial advances and retreats is understood, chronologic control is often poor with only general ages available for the inception of these events. Numerous studies have examined the stratigraphy of the lowland but it still remains poorly described due to the sheer size and remoteness of the region. As a result, correlations between beds located hundreds of kilometres apart are commonly based solely on stratigraphic position and ice-flow indicators. In addition, the fragmentary nature of the deposits in the region has resulted in multiple interpretations of the glacial stratigraphy and chronology.

Ice flow from the LIS dominated much of central Canada during the last glaciation with many lobes flowing through Ontario, Quebec, and the Prairie Provinces. Multiple glacial inception theories have been proposed. One theory suggests ice was initially land-based, advancing over the surrounding land and eventually converging and culminating in Hudson Bay (Williams, 1978). Another is that ice nucleation began in Hudson Bay and may have been synchronous with ice development on land (Denton & Hughes, 1981; 1983). However, this theory has been contested as it conflicts with paleoecologic data suggesting warmer climates during a time that would have required cold-based ice (Thorleifson et al., 1992).

The youngest flow patterns through the Hudson Bay Lowland are sporadic zones of south-southeastward flow in the Winisk-Albany area and in the Abitibi region (Fig. 1.4; Thorleifson, 1989). These flow patterns have been attributed to rapid shifts in flow direction during the deglaciation of the LIS during the very late Wisconsin (Veillette, 1986). Evidence of this SSE flow is not found in the RRA or anywhere in the Moose River Basin.
The dominant ice flow direction throughout much of the region is southwestward, which directly preceded SSE flow (Fig. 1.5). Skinner (1973) attributed the deposition of the uppermost or “Kipling Till” in the Moose River Basin to SW flowing ice as did Thorleifson (1989). In fact, the uppermost tills in many parts of the Hudson Bay Lowland and ice flow indicators from areas down-ice from the RRA in Beardmore, Geraldton and Hemlo all record SW as the dominant flow direction (Skinner, 1973; Hicock, 1988; Thorleifson, 1989). The Severn and Sky Pilot tills are stratigraphically similar units found in northern Ontario and Manitoba respectively that also show evidence of flow in this direction (Nielsen et al., 1986; Thorleifson et al., 1992). Skinner’s “Adam Till”, which underlies the Kipling and may be stratigraphically equivalent to the lower till in the RRA, is attributed to an earlier WSW ice flow. Veillette (1986) also noted striations with this old flow direction in the Abitibi region.
1.5 Previous Work

The Hudson Bay lowland has been the subject of geologic exploration for over a century. Although the RRA has only been studied in reconnaissance, much of the basic geologic background on the lowland was provided by the Geological Survey of Canada (GSC) and the Ontario Bureau of Mines near the end of the 19th century and in the early part of the 20th century. One of the earliest known geologic descriptions of the Hudson Bay region was published by Isbister (1855), but it was not until Robert Bell of the GSC (who produced over 22 geologic
reports towards the end of the century) that the geology of this region was extensively studied (Telford & Verma, 1982). Bell’s pioneering observations on the transport of glacial erratics across the lowland and into Manitoba and parts of northern Ontario is of particular significance to this thesis (Bell, 1872a, 1872b, 1887). During this period, J.B. Tyrrell also led multiple expeditions across the Hudson Bay Lowland and into the ‘Barren Lands’ in what is now Nunavut. Tyrrell (1898) described multiple till units in the lowland and linked them to specific glacial advances. He was followed by J.M. Bell (1904) who produced the first comprehensive report on the economic geology of the Moose River Basin detailing occurrences of lignite, gypsum, clay, and iron ores.

The 1920s and 1930s marked a time of heightened interest in the mineral potential of the lignites in the Moose River Basin and extensive exploration programs were commissioned by the Ontario government (Telford & Verma, 1982). The Ontario Bureau of Mines drilled over 100 holes in the region including the first to penetrate the entire sedimentary succession in the Moose River Basin (Dyer & Crozier, 1933). A thickness of 87 m was recorded but much of the top of the succession had been eroded, and therefore a true maximum thickness was not obtained. The GSC also conducted extensive studies during this time. McLearn (1927) carried out detailed studies of the Mesozoic and Pleistocene deposits and was the first to distinguish Cretaceous lignite from Quaternary peat, an issue that had confounded earlier studies. McLearn also discovered that the peat had significantly less calorific value than the lignite which limited its potential as an energy source.

Following a lull in geologic studies, the 1960s marked a time of renewed interest in the surficial geology of the region. Terasmae & Hughes (1960) studied riverbanks directly east (~ 25 km) of the RRA along the Missinaibi River and described three distinct till units. They also unearthed a sequence of peat and organic silt that was informally referred to as ‘Missinaibi beds’. Their palynologic work on these beds suggested a paleoclimate similar to the present interglacial. However, interstadial conditions were inferred as they argued an interglaciation could only occur under conditions warmer than those of present day. This interpretation was challenged by McDonald (1969) who assigned the Missinaibi beds to an interglacial based on evidence suggesting an open and ice-free Hudson Bay. Other large-scale studies conducted in the Hudson Bay lowland during the sixties included ‘Operation Kapuskasing’, a project led by the Ontario
Department of Mines which included helicopter-supported exploration of mineral resources (Bennett et al., 1967). This was followed by ‘Operation Winisk’ (Sanford et al., 1968) which included airborne geologic reconnaissance of a substantially larger area of the lowland.

Skinner (1973) provided one of the most comprehensive studies of Moose River Basin Quaternary stratigraphy. Using riverbank exposures and the Missinaibi beds he detailed four distinct members which were collectively referred to as the ‘Missinaibi Formation’. On the basis of plant and pollen assemblages that suggested a boreal forest existed in the area, an interglacial rank was inferred. Skinner also argued against Terasmae & Hughes’ (1960) assertion that higher temperatures than those at present were required for an interglaciation. Skinner also concluded there were at least five till units in the basin, two of which post-date the Missinaibi formation and were deposited during the Wisconsinan glaciation by southwestward flowing ice. Thick post-glacial deposits overlying the uppermost till were associated with a proglacial lake and eventual marine incursion of the Tyrrell Sea over isostatically depressed terrain.

Telford & Verma (1982) summarized a series of studies conducted by the OGS during the late 1970s aimed at updating and re-evaluating the mineral potential of the Moose River Basin. A series of drilling programmes and geophysical surveys revealed deposits of quartz sand, kaolinitic clay, and fire clay that were larger than previously thought. The lignite potential of the area remained inconclusive.

More recently, Allard et al. (2012) applied U-series dating on wood collected along the Nottaway River east of James Bay, which was found in a unit similar to the Missinaibi Formation. Dating yielded ages ranging from 99-119 ka thus constraining the sediments to the last interglaciation. Dube-Loubert et al. (2013) also conducted studies east of James Bay focusing on the stratigraphy and ice flow of the northeastern sector of the LIS. Their studies revealed at least five distinct till units and two prominent nonglacial units representing the last and penultimate interglaciations.
Chapter 2

2 Field Studies

2.1 Access to Area

Field work was conducted over the course of 11 days during two separate excursions in June and August 2012 to the RRA (Fig. 2.1). Planning and reconnaissance was conducted at the OGS head offices in Sudbury, Ontario during the weeks leading up to each trip. Potential sample sites were identified through analysis of various surficial maps and georeferenced SPOT imagery in ArcMap.

The nearest town to the RRA is Hearst, Ontario which lies approximately 85 km to the south and is serviced by Trans-Canada Highway #11. Travel by helicopter was the only feasible means of transportation as no roads or trails exist within the RRA. Numerous logging and forest access roads exist in the region but they extend only as far as 25 km south of the RRA and very few of these are maintained or navigable. The sheer size of the RRA (nearly 6000 km$^2$) facilitated the need for helicopter transport provided by the Ministry of Natural Resources using Eurocopter EC-130 single engine light helicopters, based at Hearst (René Fontaine) Municipal Airport.

No inhabited communities exist within the RRA although an old Hudson Bay Company post is located at Mammamattawa, located near the confluence of the Ridge and Kenogami Rivers, and is occasionally used as a cultural and ceremonial camp by the Constance Lake First Nation.
Figure 2.1 – Map of the RRA. Sample sites are marked as red triangles. Modified from Nguyen et al. 2012.
2.2 Sample Locations

The largely flat-lying drift covered landscape of the RRA has been deeply incised by an extensive network of rivers and streams resulting in large exposed sections often exceeding 20 metres in height. These exposures provide a glimpse of the underlying stratigraphy and an opportunity to obtain till samples. Although these exposures are abundant, sample sites were chosen based on a number of factors including accessibility, size, exposure, and spacing. Fieldwork preparation included examining both surficial maps and SPOT imagery in order to determine potential sample locations and appropriate landing sites (Fig. 2.2). Large areas of exposed drift along river banks were distinctive as they generally appeared as bright continuous bands along river meanders. Several hundred potential sites were identified which far exceeded the number of stops that were feasible given the time constraints. Furthermore, high water levels reduced or eliminated some potential helicopter landing zones. A total of 42 samples were ultimately collected and studied over the course of 11 days and 31 different sites in the field.

Figure 2.2 - Example of false colour SPOT imagery used during planning stages (Ministry of Natural Resources, 2013).
2.3 Sampling Technique

Each sample site was carefully examined, measured and photographed. Varying amounts of slump material covered the sites which required digging and trenching to expose a clean section (Fig. 2.3). The amount of slump cover ranged from a thin veneer on steeper sections to more than a metre on shallower ones. Multiple pilot holes were usually dug to quickly determine the underlying material and approximate the locations of major stratigraphic boundaries. Trenches were dug with shovels and grub hoes and cleaned off with small hand brushes and field knives.

Stratigraphic boundaries were measured and recorded as metres above river level. Sampling depth depended on the slope of the section but was normally within the first 1-2 m from the top of each unit. Till units lying just beneath the ground surface were usually sampled slightly deeper to avoid material which may have undergone carbonate leaching. Samples were taken from areas of exposed sections with as little post-depositional influences as possible such as oxidation and slumping. Samples weighed 1-2 kg as only textural and carbonate compositional studies were conducted; analysis for gold particles and kimberlite indicator minerals were not part of this project which would have required significantly larger samples. Approximately 50 in situ pebble to cobble sized stones were collected with each till matrix sample. The lithologies of these stones reflect up-ice bedrock sources and provide the basis for provenance studies (see Chapter 3.3 – Pebble Lithology & Provenance).

Although till is a variable sediment, the samples collected in this study are assumed to be glaciogenic in origin based on several criteria including but not limited to (Dreimanis, 1989):
1) Diamictic, poorly sorted texture.

2) Presence of distantly derived stones in the matrix that are often sub-rounded to sub-angular.

2) Glacially striated and abraded stones within and at unit boundaries including distinct bullet-shaped stones.

3) Glaciotectonic deformation structures present in subglacial tills.

Till units were generally easily identifiable in the field but some samples that were ambiguous required closer examination in a lab setting. Based on subsequent observations, several samples that were initially identified as till were reclassified. This was the case with the till sample from Site #4 which was later determined to be a glaciogenic deposit derived from glaciolacustrine or glaciomarine sediments. Also, tills that were collected at sites #23 and #30 were initially labelled as ‘middle till’ but were reclassified as flow till and upper till respectively.

While the genetic terms for tills have been the subject of much debate, genetic classification in this thesis follows Dreimanis’ (1989) criteria presented in the final report of the International Quaternary Association’s Commission on Genesis and Lithology of Glacial Quaternary Deposits. Primary tills, those that are laid down by direct glacier action, can be subdivided into various members such as lodgement, deformation, and meltout tills. Evidence of lodgement and deformation are found throughout the RRA sections (see Chapter 4.1 – Till Genesis). Lodgement tills are deposited by plastering of glacially entrained material from the base of a sliding glacier. On the other hand, deformation tills are the products of simple shear and/or subglacial squeeze flow of partially homogenized sediment. Although these are fundamentally different till forming processes, true end-member lodgement and deformation tills are rare and most tills are hybrids that fall within a continuum of till-forming processes (Hicock, 1990; Hicock & Fuller, 1995).

2.4 Till Fabrics, Structural Data & Striae

Fabric studies were carried out on each till unit by measuring stone long axes. Stones commonly have a preferred orientation associated with the direction of ice movement (Benn & Evans,
Till fabrics commonly reflect subglacial dynamics, till genesis and past ice-flow behaviour. Measurements were carried out according to the protocol of Lian & Hicock (2000) whereby the trend and plunge of the long-axis (a-axis) (Fig. 2.4) of pebble sized stones were measured using a geologic compass. These were limited to 25-30 readings per till unit per site due to time constraints; half the number of measurements usually taken. Pebbles with an a:b axial ratio greater than 3:2 were chosen so that the long-axis was easily recognized and measured.

The long-axis data were plotted on lower hemisphere equal area projection (Schmidt) diagrams in order to determine modality (Appendix G). These were plotted as points rather than contours because of the relatively low number of measurements taken per analysis. On the basis of a five-fold system of modality, Schmidt plots permit the classification of tills into two separate fields of subglacial till: a) Lodgement and meltout tills, and b) deformation till (Hicock et al. 1996). Long-axis orientations also yield eigenvalues which can also be used to infer modality. Eigenvalues are the product of the three-dimensional distribution of linear elements (long-axis orientation of pebbles in this case) and reflect how the till formed (Hicock et al., 1996). Because the subglacial environment is complex, the genetic processes of subglacial till formation exist as a continuum (Hicock, 1990) and thus, till fabrics and eigenvalues must not be used alone but rather in conjunction with other data and properties.

Glacial striations on stones were measured within (and at the base of) till units and plotted on the Schmidt plots as azimuths (Appendix G). Striations usually appear as a series of straight, parallel scratches which reflect the movement of an overriding debris-loaded glacier. Although striations are relatively small-scale erosional features they serve as important ice-flow direction indicators and can be used to determine temporal changes in regional ice-flow. Where multiple sets of striae are found, age relationships can be inferred based on the cross-cutting of one set by another and also on the relative strength of each set. The stronger and deeper striations likely belong to an older generation whereas the newer sets tend to be lighter and less robust (e.g. Hicock & Dreimanis, 1985).
The orientations of macroscale deformation structures within the till units were also recorded including shear planes, fold axial planes, and tension fractures that can be seen in sections that have been thoroughly cleaned. Analysis of glaciotectonic structures in basal tills can reveal local ice-flow directions, clues about till genesis and relationships between till facies. Strikes and dips of these planar structures were measured and plotted on Schmidt diagrams as poles to planes together with the striation and stone fabric data (Appendix G).

2.5 Stratigraphy

Numerous till units have been described throughout the lowland but only two of these were exposed in the RRA, and pre-Wisconsin deposits are rare. Till units are generally compact, silt-dominated, massive and matrix-supported with a moderate to minimal amount of stones. Deformed lenses of sand and silt are common and are evidence of sediment shearing and mixing. The till units were designated ‘upper’ or ‘lower’ and several factors were used in locally distinguishing these units including but not limited to: stratigraphic position, inferred ice-flow direction, texture, colour, stoniness, and compactness. No single parameter is diagnostic of either till and the following suggested correlations with similar units elsewhere in the lowland are the best we can do without better chronologic control. The following stratigraphic sequence for the region is presented from oldest to youngest sedimentary units. A summary of RRA Quaternary stratigraphy and suggested correlation with Skinner (1973) are illustrated in Figure 2.5. Also, several fence diagrams were constructed and can be found in Appendix E as well as stratigraphic sections for all sites in Appendix F.
Fig. 2.5: A summary of stratigraphy of the RRA and suggested correlations with Skinner (1973). Some irregular units omitted. Thicknesses not to scale.
Pre-Missinaibi Tills

Up to three tills underlying Missinaibi have been observed in the Hudson Bay Lowland (Terasmae & Hughes, 1960; Skinner, 1973). The ages of these units are largely unknown and they do not appear in the RRA. Bedrock was observed at Site #27 – the southernmost location in the RRA - which consisted of 3-4 m of highly weathered limestone (or similar carbonate), but pre-Missinaibi tills were not observed.

Organic Deposits / Missinaibi Formation

The oldest sedimentary unit found in the RRA likely correlates to Skinner’s (1973) Missinaibi Formation which includes a thick sequence of organic-rich stratified clay underlain by sand and silt found at Site #7 (Fig. 2.6). Skinner examined the Missinaibi beds in great detail and described various facies relationships, paleo-environments and subsequently assigned four distinct members; lacustrine, forest, fluvial, and marine (in increasing age). The marine unit (the oldest) was not exposed along the Ridge River or at Site #7 but is thought to reflect a marine incursion of unknown age and duration. The fluvial member reflects some interval of stream deposition after sea level dropped. This unit is subsequently overlain by the forest-peat member, an organic-rich unit representing extensive forest growth during the late stages of the nonglacial interval and prior to the formation of a proglacial lake by the advancing ice sheet which flooded the land and deposited the top lacustrine member of the Missinaibi.

Fig. 2.6: Dark stratified clay of the Missinaibi Formation at Site #7. Greenish-gray silt below shows oxidation. Arrow shows area where most of the wood was found.
Abundant sticks and branches were found at Site #7 and were pulled out of a 3 m thick bed of dark, stratified clay akin to the Missinaibi forest-peat member. This unit also contains very thin interbeds of sand and silt. Several wood samples were collected for radiocarbon dating together with samples of the sediment for future pollen analysis. This unit is underlain by approximately 0.5 m of greenish-gray nonstratified silt (Figs. 2.6, 2.7) followed by 4 m of highly oxidized interbedded sand and silt correlating to Skinner’s fluvial member. Silt intervals range from 1 cm to 5 cm thick and lack the organics found directly above.

The youngest of Skinner’s Missinaibi sequence is the lacustrine member generally consisting of laminated to massive silt and clay with some organic material. This unit is absent from Site #7 in the RRA with the lower till directly overlying stratified clay (forest-peat member). Deposition of the lacustrine member by the transgression of a proglacial lake up the
regional slope and into the RRA may not have affected Site #7 if it was beyond the limit of this lake. This assumption is speculative however as the forest-peat member is only exposed in one section in the RRA.

Radiocarbon dating of wood (Fig. 2.8) collected at Site #7 yielded one non-finite date (> 45,700 yrs.) and one finite date (46,500 yrs.). Considering the dating limit is close to the finite date, the age of the forest-peat member could potentially be greater than 46,500 years. Thus, stratigraphic position may be the only chronologic constraint. Skinner (1973) suggested determining whether the organic beds are associated with an interstadial or interglacial as a means of assigning ages. Paleoclimates as warm as or warmer than present are considered indicative of an interglaciation whereas cooler climates are linked with interstadial conditions (Skinner, 1973). There are conflicting interpretations of the paleobotanic data that support both scenarios. Analyses of pollen assemblages and identification of fossil plants and seeds were carried out by Skinner (1973) and Terasmae & Hughes (1960) and used to infer interglacial and interstadial conditions respectively. Distinguishing interstadial and interglacial intervals on the basis of palynologic data becomes increasingly difficult as one goes northward. The type of flora found in southern Ontario, for example, is much more sensitive to changes in temperature than those in the expansive boreal forests of the Hudson Bay Lowland. As a result, changes in climate and vegetation farther south are more easily detected through palynologic methods, whereas a similar change in the lowland could possibly go undetected (Terasmae & Hughes, 1960).

The discovery of these organic deposits in the RRA provides an excellent opportunity to study these beds in greater detail and to refine the chronology. While this is beyond the scope of this project, it is the subject of a Ph.D. thesis currently undertaken by April Dalton under the supervision of Dr. Sarah Finkelstein at the University of Toronto. Their project aims to determine the paleoenvironments of these deposits through palynologic studies of several organic
sites immediately north of the RRA and may indicate interglacial or interstadial rank and thereby infer their age.

**Lower / Adam Till**

The oldest till found in the RRA is the “lower till” and may correlate with the Adam till of Skinner (1973) which has also been observed throughout the Hudson Bay Lowland. This likely represents the first major Wisconsin advance in the RRA. The upper and lower tills are commonly separated by a sand/silt unit (see below) although the tills can be found in direct contact in many sections. The lower and Adam tills are massive, silt-dominated units with moderate to low stone contents. The lower till is similar both compositionally and morphologically to the upper till although it is generally more compact, less stony, and slightly finer-grained. There are no marked differences in carbonate content or stone lithologies between the two. The lower till also varies widely throughout the RRA, and therefore multiple criteria were required to distinguish and correlate these units. The upper contact of the lower till is commonly sharp with sheared overlying sediment and the occasional loose boulder concentration. In contrast, its lower contact is rarely exposed and the lower till was observed only in about 1/3 of RRA sections.

Skinner (1973) attributed Adam till to west-southwest ice flow based on striations on boulders within and at the base of the till. An early Wisconsin age was assigned by Boulton and Clark (1990) to an equivalent flow set. The stratigraphically equivalent Sachigo till, which underlies the Severn till, shows evidence of westward flow which has been inferred to be from the same advance (Fig. 1.4; Thorleifson et al., 1992). The WSW movement of ice through the RRA is also evident in the parallel set of glacial lineations seen in DEM which cross-cuts the younger southwest trending set associated with the upper till (Fig. 4.7 in Chapter 4.2).

**Inter-till Deposits**

The sand and silt unit separating the Adam and Kipling tills is known as Friday Creek sediments (Skinner, 1973). The thickness of this unit in the RRA is commonly less than a few metres (Fig. 2.9) although some sections display thicknesses of 10 m or more. No datable organic material was found within this unit in either the Moose River Basin or in the RRA. A brief late Wisconsinan ice retreat resulting in a proglacial lake has been used to explain the
genesis of these beds (Andrews et al., 1983; Skinner, 1973) while others have proposed a subglacial origin (Dredge & Nielsen, 1985). The majority of Skinner’s (1973) sections actually lack the Friday Creek sediments where Kipling till directly overlies the Adam till. Terasmae & Hughes (1960) studied exposures approximately 25 km east of the RRA and did not differentiate the Kipling and Adam tills, but simply referred to entire sequences as “Upper drift” and no inter-till sediments were mentioned. Although the inter-till sediments are fragmentary, the possibility that these were deposited in a proglacial lake cannot be ruled out. The RRA could have been near the limit of this lake if the higher elevation of the Canadian Shield bedrock in the southern part of the Ridge area was not breached. Also local variations in relief may have reduced the influence of these sediments especially if local deposition was by numerous discontinuous shallow basins near the edge of the proglacial lake.

![Fig. 2.9: Upper till overlies inter-till silt at Site #17. Lower till lies just below the silt.](image)

**Upper / Kipling Till**

The Upper/Kipling till underlies the Winisk till north of the Albany River and may be equivalent to the upper till in the RRA. Both tills are dark grayish-brown, massive, sandy-silt
units with a moderate amount of stones. Locally the upper till averages 6-7 m thick but ranges from 1-12 m thick. Sand and gravel lenses are common in the upper till whereas stone pavements are rare, generally loose and uneven. This unit varies widely and grain size and carbonate content are not diagnostic. The upper contact is mainly convoluted and difficult to discern while the lower contact is generally more distinct.

Based on stratigraphic position and flow directions the upper till may be equivalent to the Severn till in the Severn and Winisk basins of northern Ontario (Thorleifson et al., 1992), the Gods River tills (C and D of Klassen, 1986) and the Sky Pilot till (Nielsen et al., 1986), both found in north-central Manitoba. South of the Paleozoic carbonate boundary (with the Precambrian Shield) this unit is called Cochrane till (Skinner, 1973). Ice-flow direction indicators including striations, flutes, and fabrics all indicate a predominantly southwestward flow similar to what is revealed in the RRA upper till. Boulton and Clark (1990) assigned these southwest-trending drift lineation sets to extensive late Wisconsin ice flow, which is supported by Veillette’s (1986) striation data. Striations in the RRA commonly align with the regional southwestward flow although large variations do exist, which may be the effect of reworking deformable beds. The high concentration of omar greywacke erratics in the upper till is also a reflection of southwestward flow from the Belcher Islands. In addition, a clearly defined set of parallel glacial lineations is clearly seen in the RRA in DEM alongside the WSW lineations associated with the lower till.

**Winisk Till**

Previous studies have referenced at least five different till units throughout the Hudson Bay Lowland, which have been interpreted from stratigraphic position, inferred ice-flow direction, and amino acid data. The Winisk till is the uppermost till in the lowland and has only been observed north of the Albany River. It is a relatively thin unit and is considered to be the
result of a single late-stage flow (possibly southward) during the time of rapid deterioration of the LIS (Fig. 1.4; Thorleifson et al., 1992). These aspects however remain unclear and the Winisk till was not observed in the RRA.

**Post-Glacial Sediments**

Glaciolacustrine and marine sediments overlie the upper till and are exposed in more than half the sections in the RRA. These deposits predominantly consist of laminated silt and clay occasionally with marine shells, and vary from silty sand to more clayey material. The beds are mainly a few metres thick (Fig. 2.11) although some reach up to 10 m (Sites #19, #20). The silt and clay likely represent the formation of a proglacial lake by the retreating ice sheet followed by the eventual inundation of the Tyrell Sea over the isostatically depressed Hudson Bay Lowland as the northward retreating ice was breached.

The distinction between lacustrine and marine sediments is often vague with only some units containing marine shells. Marine sediments were laid down in a similar fashion to the marine member of the Missinaibi Formation that was deposited by the inundation of the Bell Sea over similarly depressed terrain during the early stages of the last interglacial/interstadial (Skinner, 1973; Terasmae & Hughes, 1960). Repeated marine inundation of the Hudson Bay Lowland during late Wisconsinan glaciation has also been theorized on the basis of amino acid data from *in situ* and transported shells although this has been the subject of debate (Andrews et al., 1983).

There are several instances where the silt and clay are preceded by a relatively thin bed of oxidized gravel and coarse sand (~ 0.5-1 m), which appear to be fluvial in origin. Gravel and sand are likely nonglacial fluvial deposits or possibly late glacial outwash and may reflect a brief interval prior to glaciolacustrine inundation (Sites #6, #10, #11, #16, #17). Moreover at Sites #5, #12, #15, and #25, instead of fluvial sediments, a convoluted zone of sand, silt, and diamicton exists at the same stratigraphic level and both the upper and lower contacts of this zone are

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**Fig. 2.11:** Both the gravel bed and the convoluted zone of till, silt and sand are exposed at Site#17 which are overlain by lacustrine silt.
mainly gradational. It is possible that this convoluted zone is the result of extensive reworking of the Winisk till that was missing from the Moose River Basin or simply a glacigenic debris flow derived from the retreating ice sheet.

**Summary of RRA Stratigraphy and Proposed Events**

- Deposition of the Missinaibi Formation during the Sangamon interglacial. After the retreat of the Bell Sea, subaerial exposure and warming supported the growth of forests in the region. These were eventually submerged and buried by a proglacial lake formed by the advance of the LIS during the early Wisconsin.
- First LIS advance during early Wisconsin deposits the lower till.
- Brief retreat during middle to late Wisconsin. Proglacial lake forms and deposits inter-till sediments in some areas.
- Upper till is deposited during a re-advance of the LIS during the Late Wisconsin.
- Deglaciation and retreat of LIS initiates a brief interval of local fluvial deposition followed by deposition of lacustrine silt in a proglacial lake dammed by retreating ice.
- Marine silts are deposited as the diminishing ice to the north is breached and inundation of the Tyrell Sea occurs.
3 Analytical Methods & Data Presentation

3.1 Particle Size Distribution

The American Society for Testing and Materials (2007) methods served as the basis for determining the particle size distribution of the till matrix samples. This methodology is based upon rates of sedimentation according to Stokes’ law which predicts the settling rate of spherical particles in water. Although variations in particle shape do affect settling rates, larger particles generally settle faster than smaller ones. An hydrometer is employed to determine the specific gravity of the suspension, which is necessary in order to calculate particle diameter. This calculation assumes a particle of the calculated diameter was at the water surface at the onset of sedimentation and has settled to the level at which the hydrometer measurement occurs at the time of reading.

According to Stokes’ Law:

\[ D = \sqrt{\frac{30 \eta L}{980 x (G_s - 1.0) x T}} \]

Where:

- \( D \) = Diameter of particle in mm
- \( \eta \) = Coefficient of viscosity of water
- \( L \) = Effective depth, the distance in cm from the surface to the level at which density readings are taken
- \( G_s \) = Specific gravity of particles
- \( T \) = Elapsed time in minutes from start of sedimentation to reading

Each sample was thoroughly disaggregated using a rubber-tipped wooden pestle after which they were passed through a 2.00 mm sieve. Exactly 50 g of the sediment that had passed through the sieve were weighed out on a balance sensitive to 0.01 g and set aside while the material caught on the sieve was discarded. The 50 g of sediment was placed in a glass beaker
and filled to the top with 0.5% sodium pyrophosphate (Na₄P₂O₇) which serves as a dispersing agent and as a stabilizer preventing particles from flocculating. The samples were stirred and left to soak for 24 hours at room temperature. Leftover sediment not part of the 50 g sample was subsequently passed through a 0.063 mm sieve for carbonate analysis.

After the 24 hour soaking, the sample was transferred to a 1 L metal cup and filled nearly to the top with more dispersing solution. Any residue on the beaker was washed into the cup with distilled water. The mixture was stirred using a milkshake machine for approximately 1 minute. Once mixing was complete, the contents were transferred to a glass cylinder and topped with dispersing solution to the 1000 ml mark. A stiff metal wire tipped with a rubber stopper was inserted into the column and used to agitate the suspension for one minute. After one minute the wire was carefully removed at which time the hydrometer time trial began.

The hydrometer readings were taken at 1 minute, 4 minutes, 15 minutes, 1 hour, 4 hours and approximately 24 hours after the time trial began. Immediately after each reading the hydrometer was placed into a control cylinder filled with 1000 ml of dispersing solution and a thermometer. Control readings were taken along with the temperature and barometric pressure which were used to determine correction factors.

After the last reading was taken the contents of the cylinder were passed through a 0.063 mm wet sieve and thoroughly cleaned with tap water to remove the < 0.063 mm portion. The remaining sediment caught on the sieve was carefully transferred to a glass beaker and left to dry. Once completely dry the sediment was passed through a sieve column stacked with 2 mm, 1mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.063 mm sieves. The column was shaken for approximately 20-30 minutes until separation was complete. The grains caught on each sieve were removed and weighed.

The hydrometer data were subsequently used to calculate the particle size distribution for each sample. Hydrometer readings in the control cylinder were subtracted from original hydrometer readings in test cylinders in order to estimate readings in distilled water which is assumed by Stokes’ Law. Elapsed time, specific gravity, and effective depth were used to determine the approximate diameters of the particles based on Stokes’ law (see above). A graph of the test results was made with particle diameters plotted on probability paper where size
fractions were determined using a clay-silt boundary of 0.002 mm (9Φ) and a silt-sand boundary of 0.063 mm (4Φ). The results are summarized in Appendix A, Figure 3.1 and in Table 3.1.

![Figure 3.1 – Ternary plot of sand, silt, and clay proportions. Corners represent 100% composition of indicated endmember size fractions.](image)

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Median</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (%)</td>
<td>33</td>
<td>32</td>
<td>72</td>
<td>17</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>54</td>
<td>55</td>
<td>68</td>
<td>26</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>13</td>
<td>12</td>
<td>35</td>
<td>2</td>
</tr>
</tbody>
</table>

*Table 3.1 – Summary table of particle size distribution.*

With the exception of a few anomalies, the majority of the samples are clustered on a ternary diagram (Fig. 3.1) suggesting a similar grain size throughout the RRA. Most samples are dominated by silt and sand whereas clay is consistently a minor component. Several outliers in the data may possibly be the result of localized lenses of coarser or finer sediment which are common in some areas. Nonetheless, these results indicate the matrix of the tills throughout the
RRA are relatively fine-grained when compared with tills from other parts of the Canadian Shield (Scott, 1976) and do not vary much between upper and lower till units.

### 3.2 Carbonate Content

The < 0.063 mm fraction of each matrix sample was analyzed for carbonate content using gasometric determination outlined by Dreimanis (1962). This method was developed while studying Pleistocene till deposits in Southern Ontario but it can be applied to other sediments containing large amounts of calcite and dolomite. Whereas particle size distribution (sand, silt, and clay fractions) provide important descriptive and statistical data, quantitative carbonate determinations can be useful in interpreting regional ice movement. Carbonates found in the till matrix are largely the result of glacial comminution and their presence in a given deposit is a reflection of up-ice bedrock lithology.

The procedure involves reacting each sample with hydrochloric acid (HCl) and twice measuring the amount of evolved CO₂ using a Chittick apparatus (Fig. 3.2). Calcite and dolomite proportions are readily distinguishable due to their different rates of dissolution in HCl. Calcite is highly reactive and is usually completely dissolved within the first 5-25 seconds depending on the size of the sample. Dolomite on the other hand reacts more slowly. Dreimanis (1962) demonstrated that the evolution of CO₂ becomes effectively nil 15-45 minutes after the start of the reaction signalling the completion of dolomite dissolution. While a small percentage of dolomite may not have been reacted by this time, the amount of evolved CO₂ during the next 30 minutes is negligible. Other carbonate minerals present in the matrix comprise a very small portion of the total weight percent when compared to calcite and dolomite and are insignificant.
Because samples in the RRA are particularly rich in carbonates, only half of the 1.7 g sample was used thus preventing the Chittick apparatus from overloading during the initial reaction. Once 0.85 g of sample was carefully measured and transferred into a decomposition flask, a magnetic micro-stirring bar and a small plastic vial containing approximately 30 ml of 20% HCl were also carefully placed inside the flask. Attention was paid to ensure that no HCl residue was present on the outside of the vial which would have prematurely triggered a reaction with the sediment. Once the vial was in place, the decomposition flask was connected to the Chittick apparatus and placed on a magnetic stirring stand. The apparatus was thoroughly checked for leaks before calibrating the manometer to zero then lowering the levelling bulb to reduce the gas pressure exerted on the system. This ensured that none of the evolved CO₂ was incorporated into the levelling solution (saturated brine).

The reaction was initiated by tilting and flicking the decomposition flask in a swift motion which caused the HCl to spill out. A stopwatch was simultaneously started and the flask was swirled in a circular motion to ensure all of the sediment was reacting with the acid. After 30 seconds the first reading was taken by aligning the meniscus in the levelling bulb with that in the manometer. Temperature and barometric pressure of the room were also noted at this time. The flask was swirled every few minutes until the reaction was complete which usually occurred 15-30 minutes after the initial reaction. It can be assumed that nearly all of the carbonate materials have been reacted to CO₂ when there is no change in the manometer reading even when the flask is vigorously shaken. The second reading was taken at this point along with the room temperature and barometric pressure. Results are summarized in Appendix B, Figure 3.3 and Table 3.2.
The majority of the samples contained between 40-50% carbonates and are loosely clustered with an average calcite to dolomite ratio of 1.5 (Fig. 3.3). Although some outliers and smaller groupings fall outside the main cluster, the upper till cannot be distinguished from the lower till based on carbonate analysis and neither till varies in carbonate content throughout the RRA. Calcite content averaged 25.5% whereas dolomite was slightly lower at 17.0% (Table 3.2). The results indicate that the tills in the RRA are highly carbonaceous and are relatively uniform in terms of carbonate content.
3.3 Pebble Lithology & Provenance

Pebble counts are commonly used to determine rock source areas and transport directions associated with till units. This technique has been widely used throughout the Hudson Bay lowland by Skinner (1973) in the Moose River Basin and more recently by Dube-Loubert et al. (2013) east of James Bay. Tracing these erratics may also be useful for drift exploration of mineral commodities (see *Chapter 4.3*). Interpretations however are complicated by the lack of detailed data in the region and the inconsistent nature of the depositional record. For this reason, stratigraphic and sedimentologic data must be used together with pebble counts.

Approximately 50 pebbles were collected from each till unit at random and were not selected based on colour, roundness, or lithology. Although cobble to boulder sized erratics were noted in the field, only pebbles were used in this analysis. The pebbles were classified into three broad categories; Carbonates, Belcher Group, and Superior Group (Fig. 3.4).

![Figure 3.4 – Pebble classification: a) Carbonates, b) Belcher Group, and c) Superior Group.](image)

These categories were chosen because they are easily identifiable and represent the largest abundances in the till samples. Local bedrock is mostly composed of Paleozoic carbonates and lacks distinctive lithologies which makes inferring local provenance difficult. Nonetheless, the dominant regional flow during the Late Wisconsinan was to the southwest. This movement transported Proterozoic Belcher Group rocks, including distinctive greywacke ‘omars’ (see *Chapter 4.2 – pg. 39*) and Archean Superior Province rocks from the south and eastern parts of Hudson Bay, respectively into the RRA. The region surrounding James Bay is underlain by Ordovician, Silurian, and Devonian limestones, dolostones, and smaller amounts of shale, evaporite, and sandstone (Skinner, 1973; refer to Fig. 1.3 for bedrock geology). A
breakdown of the pebble counts for each site can be found in Appendix C and provenance data is summarized in Figure 3.5.

![Figure 3.5](image)

**Figure 3.5** – Average pebble lithologies from RRA samples. Carbonate rocks make up an average of 66% of the pebbles whereas distal Belcher and Superior rocks comprise the remaining 34%. The “1 Till” category represents sites where only one till unit was exposed.

Locally derived carbonates are the dominant pebble type with an average of 66% in the matrix whereas Superior and Belcher group rocks average 25% and 9% respectively. There are only minor variations in pebble composition within each till unit and between the upper and lower tills in the RRA. These results suggest that local flow did not deviate drastically from the accepted regional flow. Southwestward flowing ice emanating from northern Quebec would have transported mostly carbonate pebbles from the expansive Hudson Platform and lesser amounts of Superior Group and Belcher Group erratics hundreds of kilometres down-ice to the RRA. The abundance of omars, which comprised nearly one tenth of all pebbles examined, is a strong indicator of deposition by southwest flowing ice. Omars are the colloquial name for distinctive greywackes from the Omarolluk Formation in the Belcher Islands that contain calcareous concretions and have been used to trace ice-flow paths across much of central Canada (Prest et al., 2000). These conclusions are discussed further in Chapter 4.2.
3.4 Pebble Roundness

Besides lithologic analysis for provenance, other pebble characteristics such as shape and roundness may also be helpful in inferring transport distances. Hard crystalline rocks tend to round more slowly than softer carbonate rocks. Although both shape and roundness are influenced by lithology, roundness is largely the product of the distance and duration of transport (Mills, 1979). In general most rocks increase in roundness after entrainment however, it is thought that a limiting value on roundness may eventually be reached which varies depending on lithology (Lindsey et al., 2007). For example, in a study of pebbles along the Colorado River, Sneed & Folk (1958) noted that the roundness of limestone pebbles did not increase along the entire extent of their study area because a limiting value on rounding was likely reached at some point during transport downstream. Other exceptions exist as demonstrated by their chert pebbles which did not display any marked differences in roundness at upstream or downstream sample locations. This is because chert has the tendency to break down into angular pieces during transport. Although the mechanism of transport differs, the rounding of pebbles through glacial transport generally follows the same principles.

An attempt was made to classify the pebbles collected from each sample site into one of four roundness categories: rounded, sub-rounded, sub-angular, and angular. Several established methods to systematically determine roundness exist which are generally based on measuring the diameter of curvature of the corners in the maximum projection plane (Wentworth, 1919; Wadell, 1932; Krumbein, 1941; Cailleux, 1947). However, image comparison charts were used to classify the pebbles from the RRA instead of quantitative methods. This was done to assess the feasibility of using roundness to aid provenance studies in the RRA.

Pebbles collected from each sample site were carefully separated based on roundness (Table 3.3; raw data in Appendix D). The majority of the pebbles were sub-angular to sub-rounded, representing almost 95% of the total. Sub-angular pebbles are dominant throughout the RRA with over 70% of the total and only about 5% of all pebbles on average were truly rounded or angular.
There are numerous difficulties with this method. First, the distinction between the four roundness categories is not always clear and results are subjective. In fact, even when quantitative methods are employed, different investigators will produce different results due to the subjectivity involved (Folk, 1972). In addition, the vast majority of pebbles from RRA samples are carbonates of the Hudson Platform which extends hundreds of kilometres up-ice of the RRA. As a result, the distinction between locally and distantly derived carbonates is often unclear especially if a limiting value on roundness is achieved (Lindsey et al., 2007). Furthermore, the nature of glacial transport can be a complicating factor as the addition of fresh, angular, englacially-transported rocks may skew downstream rounding during extended ice flow.

Although roundness of RRA pebbles was determined to infer transport distances, the results were inconclusive in distinguishing local from distantly-derived stones based on roundness alone (Table 3.3). However, among the RRA pebbles there are abundant sub-angular shield rocks originally from Quebec that have been glacially transported thousands of kilometres to the RRA.

### Table 3.3 – Summary table for roundness of pebbles from till in the RRA

<table>
<thead>
<tr>
<th></th>
<th>Rounded</th>
<th>Sub-Rounded</th>
<th>Sub-Angular</th>
<th>Angular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average # of pebbles per sample</strong></td>
<td>1.7</td>
<td>14.7</td>
<td>44.2</td>
<td>1.9</td>
<td>62.5</td>
</tr>
<tr>
<td><strong>Average percent</strong></td>
<td>2.7%</td>
<td>23.5%</td>
<td>70.7%</td>
<td>3.0%</td>
<td></td>
</tr>
</tbody>
</table>
4 Interpretation of Results & Discussion

4.1 Till Genesis

Evidence gathered from field studies and from detailed analyses on the RRA samples suggests a complex history of till deposition involving both lodgement and deformation. Although deformation and lodgement tills can appear identical they can be distinguished on the basis of stone orientations (fabrics), glaciotectonic structures, and striations on stones (Dreimanis, 1989; Hicock & Fuller, 1995). Complex sediment successions require multiple criteria in order to interpret genetic relationships (Hicock, 1992; Benn & Evans, 2010). Although the oscillation of the ice margin during the Wisconsin has contributed to the change in till facies, this change is not always represented as discrete units, but rather superimposed upon each other. Rheologic superposition is a model whereby successive sequences of till facies overlap and may explain the variation in the RRA fabric and structural data. Overprinting of till characteristics representing different deformational histories can occur as the subglacial material shifts from brittle to ductile deformation and vice versa (Hicock, 1992).

The RRA stone fabrics are commonly weak and display girdle to polymodal patterns. Stone striations, although loosely oriented NE-SW, are also transverse to ice flow, and stone striation directions commonly differ from fabric orientations (Fig. 4.1). Hicock & Dreimanis (1985) and Dreimanis (1989) found that tension fractures dip steeply down-ice whereas shear planes dip shallowly up-ice or down-ice. Both are commonly caused by simple shear during lodgement, and are consistent with fabric and striation orientations. However, poles to tension fractures
and shears in the RRA plots are variable and not always consistent with stone striations or fabrics. Together these results suggest deformational overprinting of what started as lodgement deposition. This may also be the case with the stone concentrations observed at Sites #3 and #8 which possess striations in various orientations. An increase in till pore water pressure would decrease its shear strength leading to a material that would be easily deformed by overriding ice. This would allow the stones to rotate and end up in various orientations (Fig. 4.2). This would also explain the weak fabrics that are prevalent in the RRA. Increased pore water pressure may allow reorientation of the pebbles during a change in rheologic state from brittle to ductile (Hicock & Fuller, 1995). Data from upper and lower tills in the RRA are comparable suggesting similar depositional conditions and histories. These conditions would also be conducive to rapid flow and ice streaming as the overriding glacier would have travelled over soft muddy substrate (see Chapter – 4.2).

![Figure 4.2. Rheologic superposition in subglacial till](image)

**Figure 4.2.** Rheologic superposition in subglacial till **A:** Ductile deformation (squeeze flow) occurs in saturated till as pore water pressure is high. Stones may become displaced from their original position/orientation. **B:** As pore water content decreases the deforming till stiffens and brittle deformation (by simple shear) occurs. A new rheologic state is superimposed on the deforming till (Modified from Hicock, 1992).

### 4.2 Implications for Ice Streaming

Ice streams are areas of relatively fast-moving ice bounded by slower-moving ice (Benn & Evans, 2010). Rapid-flow is generally achieved through high basal lubrication provided by high pore water pressure and/or weak tills (or bedrock) susceptible to deformation and shear. Because criteria are still being established to recognize former ice streams it is often difficult to
objectively prove their existence in a given area. Lines of argument commonly include glaciologic principles and using contemporary ice streams as modern analogues. Late Wisconsin ice streaming through the RRA is plausible based on the following evidence:

1. **Abundance of distantly derived stones in till matrix**

   The RRA lies mainly on a thick sequence of unmetamorphosed, gently dipping carbonates that stretch for hundreds of kilometres north and northeast through Hudson Bay (Shilts, 1980). Although the RRA lies predominantly on these carbonates, distal Belcher and Superior erratics comprise an average of 24% of the pebbles collected (Fig. 3.5 in *Chapter 3.3*). This abundance of distal material is significant considering they are sourced in areas hundreds of kilometres up ice. The abundance and lithologies of these erratics remain fairly consistent throughout the RRA. In addition, there is no significant difference in abundance between the upper and lower tills, suggesting similar transport directions and mechanisms.

   Distinct erratics derived from the Omarolluk Formation from the Belcher Group are common throughout the RRA. These erratics are informally referred to as “omars” and are generally massive dark grey siliceous greywackes characterized by concentric calcareous concretions (Fig. 4.3; Prest et al., 2000). They originate in the southern part of Hudson Bay, 700 kilometres to the northeast of the RRA. Although similar greywackes exist elsewhere in the Canadian Shield (e.g. Chelmsford Formation in the Sudbury Basin) and also contain calcareous concretions, they are not likely to be found in the RRA as they are not sourced to an area up ice of the RRA. Based on Late Wisconsinan ice-flow patterns and the distribution of these omars, a single source area is responsible for the regional dispersal in the Hudson Bay Lowland (Prest et al., 2000). Several criteria were used in recognizing omars which include but were not limited to:

   - Dark, massive, fine-grained, and siliceous; in stark contrast to the carbonates
   - Presence of spherical calcareous concretions weathered to varying degrees

Figure 4.3 – Example of a large striated omar bullet stone with a distinctive calcareous concretion.
• Little evidence of significant metamorphism or deformation

Although the presence of omars alone does not imply rapid ice flow, the abundance of distal erratics hundreds of kilometres down-ice from their source areas reflects a large sediment flux by the advancing glacier. Furthermore, a significant proportion of these distal erratics are sub-angular which suggests rapid transport from their source areas with minor comminution over a large distance.

Hicock (1988) found similar occurrences of omars down-ice of the RRA in the Geraldton and Hemlo areas. There, a wide band of highly calcareous drift is bounded by zones of non-calcareous drift which is akin to what Dyke & Morris (1988) referred to as “Boothia-type” dispersal (Fig. 4.4). They concluded that this type of dispersal train is highly suggestive of ice streaming due to its sharply convergent margins and the long distance transport of erratics within it. Boothia-type dispersal however, should be used with other lines of evidence to support the presence of ice-streaming.

Dispersal in the RRA cannot be assigned to either the fast moving Boothia-type or slower moving Dubawnt-type (Fig. 4.4). However, if the abundance of distal erratics in the RRA can be attributed to Hicock’s (1988) proposed ice stream then the margins of the ice stream may be wider than what is shown in Figure 4.5 and may either partially or fully encompass the RRA.
2. Fine grained till derived from carbonate bedrock of the Hudson Bay Lowland, which extends hundreds of kilometres up-ice, supports high subglacial pore water pressure

As ice sheet dynamics are intimately linked to subglacial bedrock geology, it is understood that soft sedimentary beds provide more lubrication for basal sliding and are therefore more conducive to ice streaming than crystalline bedrock (e.g. Hicock et al., 1989). This is due in part to the fine-grained texture of soft beds, which supports high basal water pressure and low frictional resistance that may produce highly deformable tills. Modern-day analogues in west Antarctica support this theory where seismic observations have shown that the velocity of ice flow is highly dependent on the subglacial geology wherein fast flowing ice occurs over soft-bedded areas (e.g. Anandakrishnan et al., 1998). In addition, ice that has advanced over soft beds generally travels farther than ice over coarser crystalline bedrock (Patterson, 1998). These glaciers also tend to produce finer clay and silt deposits supporting even greater pore water pressure (i.e. positive feedback process).

Particle size analysis of the <2 mm size fraction of the RRA samples yielded an average distribution of 54% silt, 33% sand, and 13% clay (i.e. 67% mud; see Chapter 3.1). There is very little variation spatially between upper and lower tills, thus carbonate-rich silt till dominates throughout the RRA. Figure 4.6 shows a textural comparison of tills attributed to ice streaming.
and those that are not (Lian et al., 2003). The average of the RRA samples plots within the field of inferred ice streaming which is clearly more finely grained than the cluster of samples with no ice stream inferred.

![Figure 4.6](image)

Figure 4.6: Comparison of texture in tills attributed to ice streaming with texture of till in bounding areas. Modified from Lian et al. (2003).

Although the occurrence of ice streaming in the LIS is closely linked to soft-bedded areas, it is not a requirement as fast flowing ice can spread fine lubricating till over hard-bedded areas (e.g. Dubawnt Lake ice stream and in the Hemlo area). It is difficult therefore, to determine the degree to which bedrock geology alone controls rapid ice-flow. Several ice sheet models have demonstrated that neither soft beds nor topographic troughs are necessary for ice streaming (Payne & Baldwin, 1999; Stokes & Clark, 2003). It has been suggested that interactions between an ice sheet’s internal glaciologic dynamics such as flow, form, temperature and mass-balance may initiate rapid flow over areas not thought to be conducive to ice streaming (Stokes & Clark, 1999). Nonetheless, there is little doubt that certain bedrock lithologies are conducive to ice streaming.
3. **The presence of elongated subglacial bedforms - mega-scale glacial lineations**

These ridge-groove structures are similar to drumlins and flutes but are much larger, more elongate, and longitudinally aligned (Clark et al., 2003). Their high elongation ratios, sometimes up to 100:1, have been used to infer ice streaming elsewhere (Clark, 1993; Clark et al., 2003; Stokes & Clark, 2003). Two sets of irregularly spaced lineations are preserved in the RRA and are easily visible on the digital surface model (DSM, Fig. 4.7). One set is aligned WSW which correlates to the dominant ice-flow trend in Skinner’s (1973) Adam Till and has also been observed using satellite images by Boulton & Clark (1990). The second major set trends SW and parallels the dominant ice flow direction in the region. This flow followed the WSW flow and is recorded in the upper tills throughout the Hudson Bay Lowland (Skinner, 1973).

The sets cross-cut indicating a shift in flow direction and possibly a synchronous shifting of a dome within the LIS (Boulton & Clark, 1990). Some lineations exceed 20 km long and closely resemble those of the Dubawnt Lake ice stream (Stokes & Clark, 2003). Contemporary analogues also show nearly identical linear bedforms over soft-bedded areas in west Antarctic ice streams (Wellner et al., 2001).

![Figure 4.7: Digital surface model (DSM) of the RRA. Several prominent large-scale glacial lineations have been highlighted with black lines. Two distinct lineation trends are visible (Modified from Ontario Ministry of Natural Resources, 2010). Projection system: NAD 1983 Lambert Conformal Conic.](image-url)
4. **Pebble fabrics consistently yielding polymodal fabrics coupled with low eigenvalues (S₁~0.56) suggests a significant component of subglacial ductile flow**

Pebble fabrics from the RRA were carefully analyzed and classified based on a five-fold scheme of modality outlined in Hicock et al. (1996). A majority of RRA samples produced polymodal to girdle-like fabrics with only a couple of spread bimodal exceptions (8L, 9L) and one spread unimodal (11; Appendix G). These are consistent with deformation tills which have generally weak fabrics and eigenvalues. Tills can be classified into one of two domains based on modality; 1) lodgement and meltout tills which tend to produce stronger fabrics, and 2) deformation tills which are associated with weaker fabrics.

Deformation tills are characterized by ductile flow controlled mainly by till pore water pressure, matrix texture, and stone content (Hicock & Dreimanis, 1992). If soft carbonate tills in a region are able to sustain enough pore water for ductile flow then these areas should be conducive to rapid ice flow (Hicock & Dreimanis, 1992). The cumulative effect of high pore water pressure, fine carbonate tills, and easily deformable beds would render the basal till too weak to resist the basal shear stress of overriding ice, enabling rapid flow.

Ductile flow and shear may explain the weak fabrics and inconsistent stone striae throughout the RRA. While only 25-30 long-axis measurements were taken for each sample due to time constraints, the consistently low eigenvalues and weak fabrics produced are notable even with a relatively small sample size. In addition, stone striae throughout the RRA vary widely and only display a loose trend parallel to the regional ice flow (SW) which may reflect the instability of the overridden beds. The S₃-S₁ plot introduced by May et al. (1980; Fig. 4.8) is used to relate eigenvalue ratios to end-member tills. The RRA samples plot largely within the field for glaciogenic sediment flow with some samples plotting in the overlapping field of lodgement till. The latter samples may have started out as lodgement tills which subsequently experienced some component of deformation by ductile shear and/or squeeze flow with increased pore water pressure (Hicock et al., 1996). The few discrete shears observed in till in the RRA may be the result of localized lodgement undergoing simple shear prior to increasing pore water pressure and rheologic superposition resulting in ductile shear in a deforming bed (e.g. Hicock 1992; Hicock and Fuller 1995).
As stated above, rapid ice flow can also be initiated by glaciogenic controls and ice-streaming can also occur over hard-bedded areas. In fact, Hicock (1988) inferred a southwest flowing ice stream through the Albany Valley directly down ice from the RRA (Fig. 4.5). Despite the fact that this area is underlain by a hard-bed of crystalline Shield rocks, a broad topographic trough in the region may have been the conduit for ice streaming. If we correlate the ice stream from the RRA to that of Hicock (1988), the ice-stream margins would likely be wider up-ice than is portrayed in Figure 4.5.

4.3 Potential for Mineral Exploration

A thorough knowledge of glacial geology is essential when prospecting for mineral deposits on terrain covered by glacial drift. Whereas “traditional” geochemical assays depend on elements that have been transported from primary and/or secondary sources through liquids, gases or other chemical processes, drift prospecting is based solely on mechanical processes that have transported mineral grains. Therefore, reconstructing subglacial processes in the RRA is necessary for interpreting the composition, thickness and erodibility of drift units along with
bedrock geology and regional flow directions (Thorleifson, 2013). The dispersal of certain indicator minerals, including those from kimberlites, sulphides and gold grains, may be traceable for hundreds of kilometres down-ice. Although searching for these indicator minerals in the RRA was not part of this project, the work conducted here may serve as a foundation for future exploration of a wide range of commodities in this sparsely studied region.

Based on the information presented, the writer concludes that drift prospecting as part of a mineral exploration program would not be effective for the following reasons:

- Carbonate bedrock is widespread and extends for hundreds of kilometres up-ice of the RRA. Although the study area lies at the margin of the Canadian Shield, the predominant southwestward flow direction would not have transported any relevant indicator minerals through the RRA. Localized ice flow can be highly complex and may differ from regional ice flow patterns however the principal up-ice area would still be underlain by carbonates. Furthermore, the most recent ice flow direction, a south-southeastward movement found mainly in the Abitibi region, does not appear to have affected the RRA, nor did it affect Veillette’s (1986) area in Quebec.

- Indicator minerals found in our samples would have likely been subjected to long distance transport originating along the eastern shore of Hudson Bay. Over those distances it is difficult detect a meaningful dispersal train. The sheer distance travelled would also have been enough to dilute elemental abundances beyond detectable limits. In fact, Thorleifson and Kristjansson (1990) noted that even with rapid ice flow through the Beardmore-Geraldton area, long distance transport over carbonate bedrock have rendered mineralized debris too dilute to detect beyond a few kilometres from their source.
Chapter 5

5 Conclusions

As stratigraphic records in the Hudson Bay Lowland remain fragmentary and have not been well constrained chronologically, studies in the remote RRA are an important first step towards resolving these discrepancies. New information from this project has improved our understanding of the subglacial dynamics of the LIS during the last glaciation and these efforts contribute to the Quaternary stratigraphic framework of the region. Future studies in the region could focus on areas north of the RRA especially where other organic sections and pre-Missinaibi tills are found. Based on the results of the RRA study the following conclusions can be drawn:

- The organic-rich unit at Site #7 likely correlates to Skinner’s (1973) Missinaibi Formation and the Sangamonian interglaciation. Post-Missinaibi sediments were deposited by the repeated advance and retreat of the LIS during the Wisconsin glaciation.

- Two till units (upper and lower) are found in the RRA which were deposited by SW and WSW ice flow during the Wisconsin. These tills are carbonate-rich, muddy, and contain abundant distantly derived stones.

- Stone fabrics, striations, and glaciotectonic structures suggest that significant ductile deformation (by squeeze flow) occurred during till deposition.

- Both upper and lower tills were subjected to varying degrees of lodgement and deformation during their formation as rheologic states were superimposed over space and time.

- Paleo-ice streaming through the RRA is plausible as conditions were favourable for rapid flow.

- Drift prospecting of economic minerals would not be effective in the RRA due to the direction of ice flow during the last glaciation and the vast up-ice expanse of carbonate bedrock.


Krumbein, W.C., 1941. The effects of abrasion on the size, shape and roundness of rock fragments: Geology, v.49, p. 482-520.


Appendices

Appendix A: Summary of particle size distribution.

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### Appendix B: Summary of Carbonate Analysis

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Appendix E: Fence diagrams. Far-left scale is metres above sea level.
Appendix F: Stratigraphic Sections. Vertical scale is in metres above river level.
Appendix G: Equal area (Schmidt) Projections. Dots = stone long axis orientations, Azimuths = stone striations, Triangles = poles to shear planes, Squares = poles to fold axial planes
Curriculum Vitae

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L. Austin Weeks Undergraduate Grant (AAPG) - 2011
Mark A. Turner Memorial Scholarship in Geology (UWO) - 2010
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2012-2013

Teaching Assistant
The University of Western Ontario
2011-2013

Junior Geologist
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2011

Publications:
