TESTING THE APPLICATION OF COSMOGENIC ^{10}Be AS A TRACER FOR SUBGLACIAL PROCESSES IN TILL AT CONRAD'S HEAD, NOVA SCOTIA

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Abstract

The Hartlen Till is an extensive, variably thick (> 20 m), highly compacted, grey silty diamicton that cores many of the drumlins exposed along the eastern shore of central Nova Scotia. Due to its apparent homogeneity, many of the observations made at specific locations are transferrable to other outcrops. Based on ice flow measurements, pebble provenance, and offshore stratigraphy, it has been previously determined that the till was deposited during the Caledonian glacial phase. As it commonly occurs at the base of the terrestrial stacks of tills, it may comprise material from the Meguma and associated terrains that had been previously exposed to cosmic rays for a prolonged period of time. Based on previous measurements of ^{10}Be in till, it is assumed that the Hartlen quartz sand contains inherited ^{10}Be from exposure as regolith prior to its deposition. The till therefore provides an ideal means of demonstrating the plausibility of a deformable bed in a drumlin environment using cosmogenic isotopes.

Although the concept of deformable beds accounting for a significant portion of the movement beneath glaciers is generally accepted, the thickness and contribution of a deforming bed at a given time is less predictable, varying with the material properties of the bed, flow velocity, and subglacial hydrology conditions. The thickness of a deforming bed has only been observed under modern glaciers. Our experiment uses a vertical sequence of eight samples of quartz sand from the Hartlen Till matrix. It was found that there was little variation in the concentrations of^{10}Be within the Hartlen Till, but the ^{10}Be concentration in the base of the Lawrencetown Till was four to five times smaller. We can infer that the interglacial period that occurred before the Caledonia Phase (early Wisconsinan) was a long enough period of exposure to produce concentrations on the order of $\sim 7.0 \times 10^4$ atoms g^{-1} in the Hartlen Till. This also suggests that the period between the deposition of the Hartlen and Lawrencetown tills was significantly shorter, producing concentrations of $\sim 1.5 \times 10^4$ atoms g^{-1} in the Lawrencetown Till. The vertical trend in the Hartlen till allows us to assume that the deformable bed can reach a thickness of at least 5m, which corresponds well with previous studies of the deformable bed.

Keywords: deformable bed, cosmogenic nuclides, till genesis, interglacial, Caledonia Phase.

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1.0 Introduction

1.1 Introduction to the Problem

Glaciers formerly covered a significant portion of the polar and temperate land regions of the planet and created many of the landscape features observed today in Canada. Glacial ice currently only makes up approximately ten percent of modern day Earth's land surface, and yet still has a substantial impact on landscape development (Benn and Evans, 1998). It is important to determine how glaciers erode, how till is produced and transported, and what role till plays in the dynamics of different glaciers, particularly ice sheets because of their vast volumes and impact on oceanography and the drift exploration industry.

The relationship between a glacier and its bed controls glacier dynamics at different time and space scales (Alley, et al., 1986). It has been challenging to develop a general rule that describes how a glacier interacts with its substrate material. The difficulty is partly due to significant differences in glacier type, subglacial processes and hydrology, substrate material properties (particularly shear strength), and temporal variations in these dynamics as the glacier system responses to forces related to climate or sea level change. Part of the challenge arises from the difficulty in directly observing ice-bed interactions in a wide range of modern glacial environments.

By studying the relationship between an ice sheet and the material beneath it, implications of large-scale glacial processes can be made. Till genesis is an extensive area of research, but there are still uncertainties involved in subglacial dynamics. Accurate thermo-mechanical models require knowledge of the substrate, including composition, thermal regime, thickness, water content and pressure, and resistance to various stresses.

For example, Heinrich events in the northern Atlantic Ocean occurred when large quantities of ice-rafted sediments appeared in the marine sedimentary record at regular intervals of approximately 8-10 ka (Broecker et al., 1992). This has been attributed to rapid melting periods from surges within the Laurentide ice sheet. These surges are likely a result of instability in the subglacial soft sediments (Clark, Alley and Pollard, 1999). Massive meltwater outputs can also be attributed to surges within the ice sheet, demonstrating the impact of subglacial dynamics. Unconsolidated sediments beneath a glacier can behave variably depending on the ice basal thermal regime, grain size, porosity and interaction with water.

This paper concerns a subglacial feature known as the deformable bed. This bed is a mass of unconsolidated sediments that experiences shearing from the stress of the overlying glacier and contributes significantly to the net velocity of glacier ice. This sediment layer is poorly understood, especially in post-glacial tills where the interaction between a glacier and its bed is no longer directly observable.

From an applied geoscience point of view, a better understanding of deformable beds is important for overcoming difficulties in mineral exploration in glaciated regions. Glaciers and ice sheets are able to erode and transport surface materials, which can contain economic deposits in mineralized terrains. For example, pre-glacial placer gold deposits in northern Canada were likely subjected to glacial activity during the Last Glacial Maximum. Placer deposits are not only found proximal to the surface, but are typically fine grained. Surficial materials can be easily transported by glacial ice, and fine-grained material is more prone to erosion. This logic can be applied to other surficial mineral deposits in any glaciated region. Once it is understood how substrate becomes eroded and transported,

uncertainty is reduced when attempting to locate and extract minerals in these ice-covered areas.

The deformable bed has been recognized in the subglacial environment (Murray, 1997; Waller, 2001; Knight, 2010) and it has been determined that a deformable bed must have a maximum thickness before becoming unstable (Boulton and Jones, 1979). But, other than its existence, little is known in terms of its thickness or how much influence it has on the movement of a glacier. Recognizing that deformation of sediment under the ice will contribute to additional velocity, it is reasonable to predict that thicker deformable beds contribute more velocity than thin beds. It is further possible that recognition of thick deformable beds in ancient tills could help guide estimates of paleo-ice velocities. Although observed in modern subglacial environments, the deformable bed in ancient tills is more difficult to recognize. The purpose of this research is to determine if cosmogenic nuclides can be used to indicate the presence of a deformable bed in previously deposited tills.

1.2 Testing ^{10}Be as a Tracer of Subglacial Processes

Terrestrial cosmogenic nuclide (TCN) methods are commonly used for exposure dating, but can also be used as a tracer for a variety of geologic processes. ^{10}Be, a widely used TCN, has been used to distinguish the basal thermal regime of a former glaciated site in Baffin Island (Staiger et al., 2006). It was found that till under weakly-erosive cold-based glaciers tends to have a higher ^{10}Be concentration inherited from exposure prior to glaciation. The purpose of this study is to develop a method to help delineate the thickness of a deformable bed under different ice and substrate conditions. ^{10}Be will be analyzed by means of accelerator mass spectrometry (AMS) in the Hartlen and Lawrencetown tills at a

site in West Lawrencetown, NS, in order to determine if there is evidence of a deformable bed. Samples will be taken vertically from a drumlin site where tills are sufficiently thick and easily accessed, and where some other interesting questions may be addressed, such as the age of the Hartlen till. The AMS analysis may also provide insight into the origin of the stone line between the Hartlen and overlying Lawrencetown tills, as well as settle the debate as to whether an interglacial period took place between the deposition of these two tills.

1.3 Hypotheses

Although the long-term objective is to improve our understanding of till production, transportation, and deposition, the short-term objective is to test the following hypotheses: (H1) The Hartlen till will have a higher inherited concentration of ^{10}Be than the overlying Lawrencetown till. The large-scale glacial stratigraphy of Nova Scotia has been recently revised (e.g. Stea and Pe-Piper, 1999; and Stea 2004; Stea et al., 2011). It is established that the Hartlen till was the first Wisconsinan till to be deposited in the region, after the approximately 60 ka Oxygen Isotope Stage (OIS) 5 interglacial period (Stea, 2004). Through the work established by Staiger et al. (2006), it can be inferred that this prolonged interglacial period would be sufficient to produce a measureable amount of cosmogenic ^{10}Be in the regolith that is later incorporated into the Hartlen till. Alternatively, the Lawrencetown till is a late Wisconsin deposit comprising regolith that would have had a much shorter pre-glacial exposure duration. (H2) When a depth vs. ^{10}Be concentration profile is constructed from the AMS data, the trend can be used to determine if the Hartlen

till had a deformable bed. The vertical concentration vs. depth profile can have five possible outcomes (Fig. 1.1):

(i) the ^{10}Be concentrations can be uniform with depth, indicating a well-mixed till or a very thick deformable bed;

(ii) the ^{10}Be concentration can increase toward the base of the till. This would indicate that the source material at the regolith surface was deposited first and had the highest concentrations due to the attenuation of cosmic ray flux through the regolith, and therefore that the thickness of the deformable bed was less than the thickness of the Hartlen till (which at the study area is > 5 m);

(iii) the ^{10}Be concentrations could be highest at the top of the Hartlen till, which would indicate a well-mixed till with a thick deformable bed, subsequently exposed during an extended interglacial period. As the ice retreated from the area for a period of time, the newly deposited till would have accumulated higher ^{10}Be concentrations due to exposure;

(iv) the ^{10}Be concentration could be high at both the base and the top of the profile. This would indicate that a combination of both (ii) and (iii) had occurred; and finally,

(v) the ^{10}Be concentrations may have no vertical pattern at all, is variable beyond the precision of the measurements, which would indicate a till that was not well-mixed and would indicate that either the isotopes cannot be used to determine the presence of a deformable bed, or a deformable bed was not present, or perhaps that an error in sampling or AMS analysis was not recognized.

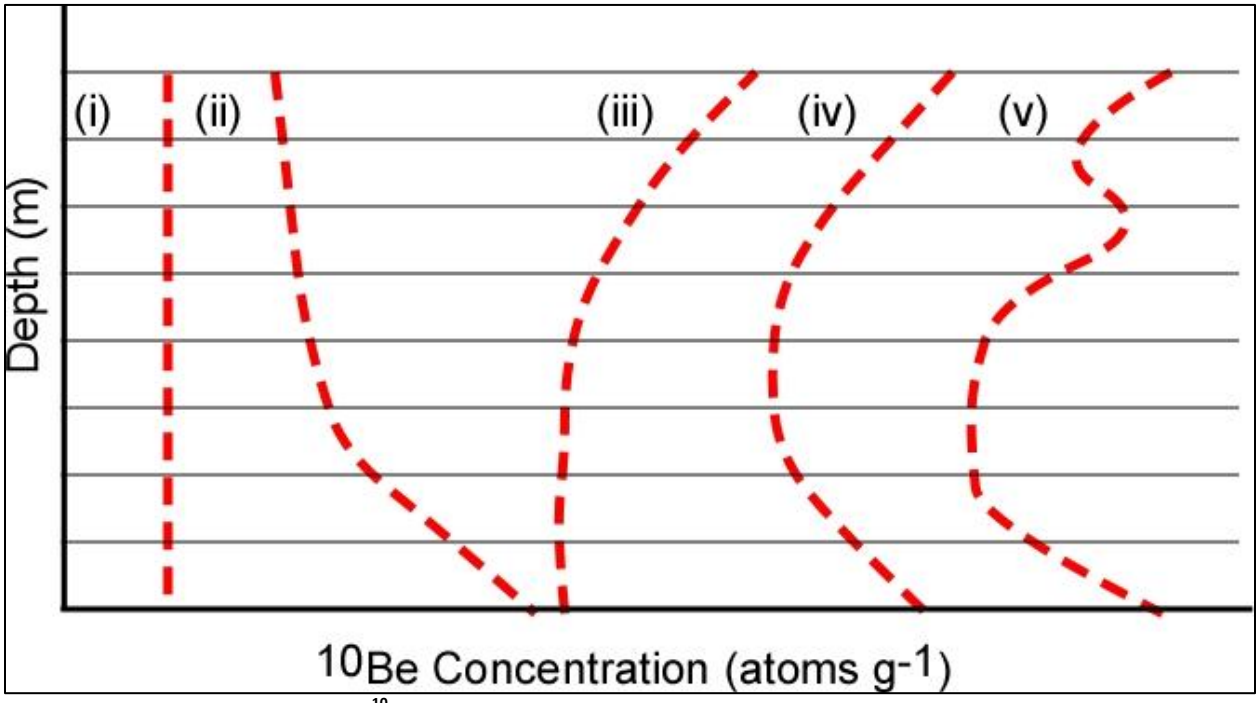

Figure 1.1: Possible outcomes of the ^{10}Be concentration vs. depth profile. Each horizontal line represents the relative position of a till sample.

1.4 Study Area

The study site is a 15 m coastal section through a drumlin in West Lawrencetown known as Conrad's Head (Stea and Pe-Piper, 1999), on the eastern shore of Nova Scotia (44.64°N and 63.36°W) (Fig. 1.2) There are three tills exposed in the drumlin, the oldest being the Hartlen Till, which is overlain by the Lawrencetown till at a sharp contact (Fig. 1.3). The third till, which is thin and less distinct than the Hartlen and Lawrencetown, has been interpreted as a reworked section of the upper Lawrencetown till that occurred during the Scotian phase (20-17 ka) of Wisconsinan glaciation (Stea et al., 2011). The Hartlen till is a compacted, grey till with a silt-rich matrix and forms a steep sea cliff slope. The high erratic content in the Hartlen till has been useful in determining the source of the till. It contains 59% metagreywackes from the underlying Cambrian-Ordovician Meguma Group, 23% white, local granitic pebbles, and 17% non-Meguma clasts that include North Mountain basalt erratics as well as other volcanics (Stea and Pe-Piper, 1999). The base of the Hartlen Till is concealed under the cobble beach at Conrad's Head, and therefore its total thickness and till properties below beach level are unknown. The overlying, red Lawrencetown till is less compact with a coarser grained matrix, resulting in a shallower topographic slope, presumably due to a reduced coefficient of friction. The Lawrencetown till coarsens upward, which could be indicative of mixing with Hartlen till that it initially incorporated. The Lawrencetown till has a relatively higher erratic content (>50%) (Stea and Pe-Piper, 1999).

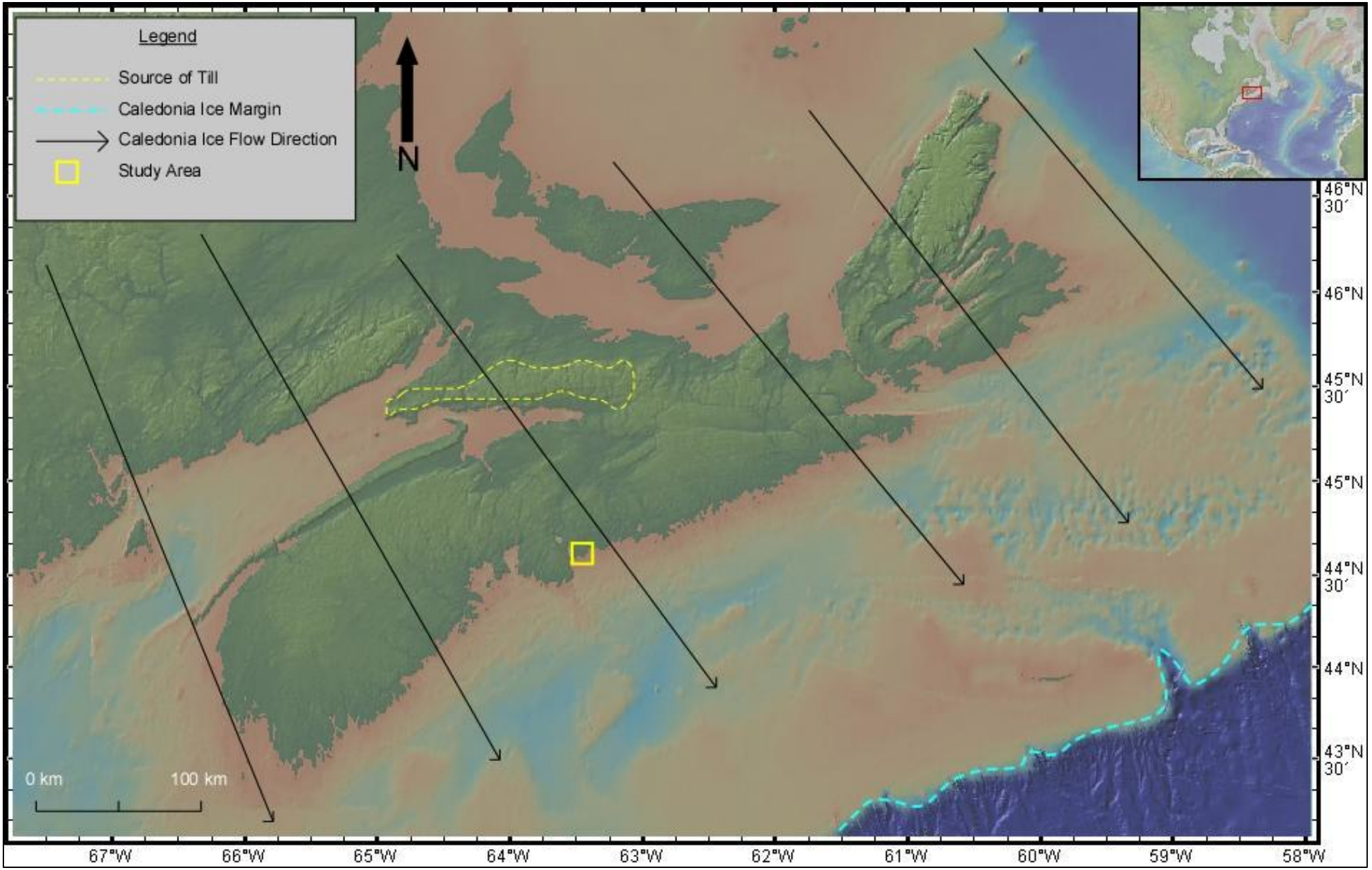

Figure 1.2: Bathymetric and Topographic Map of Nova Scotia showing Caledonia Phase glacial flow lines and ice margin. The study area and till source is also shown. (Base map provided by http://www.geomapapp.org, 2012).

Figure 1.3: Photograph of the Conrad's Head drumlin section. The Hartlen Till is the lower grey unit, and the Lawrencetown Till is the upper red unit. Photo credit, D. Midwinter

Exposed bedrock on the western section of the drumlin displays striations representing two distinct flow directions. The older set of striations (originating from the Caledonia phase glaciation) trends 150° in a southeast direction, while the younger set trends 185° in a more southern direction (Stea and Pe-Piper, 1999). The Lawrencetown Till has clast origins in the Hart Lake-Byers Lake pluton near Debert, NS, in the eastern Cobequid Highlands, while the Hartlen Till contains erratics from the western Cobequid Highlands as well as clasts of North Mountain Basalt origin which was determined by geochemical analysis of the clasts (Stea and Pe-Piper, 1999).

The till section contains two distinct, lateral planes of large boulders and cobbles that extrude from the till matrix as a result of erosion. There are several terms used to describe these boulder layers, and they will be referred to throughout this paper as 'stone lines'. A stone line can be defined as "a three-dimensional layer of stones about one stone thick, with a consistently striated surface, which crops out as a line in a near- vertical till exposure, with spaces between stones filled mainly by till matrix" (Hicock, 1991). One stone line occurs at the base of the Lawrencetown till, centimeters above the contact. The other can be found 2-3 m above the first, also within the Lawrencetown till. The stone lines could have formed from: (i) a deflation surface resulting from an extended interglacial period that occurred between the deposition of the Hartlen and Lawrencetown tills. In this instance, sediments were deposited above the Hartlen till, and the fine-grained sediments were subsequently eroded away by wind or water, leaving behind only the large boulders. (ii) a lag deposit from the erosion of the Lawrencetown till material during its deposition. A lag deposit develops in a similar manner to a deflation surface, however instead of wind or

water causing erosion, the overlying glacier entrains the fine-grained sediment and leaves behind the large boulders.

In summary, the Conrad's Head drumlin section provides easy access to a till that is apparently geochemically, sedimentologically, and lithologically uniform with depth, permitting a test of the idea of using ^{10}Be to determine the thickness of a deformable bed in an ancient till. It also provides an opportunity to verify the Oxygen Isotope Stage 4 age of the Hartlen till, and evaluate the difference between two tills with similar source elevations but differ in the durations of the interglacials that precede them.

2.0 Background

2.1 Till Deposition

A till is sediment that is deposited directly by glacier ice. It typically comprises a massive matrix-supported, poorly sorted diamicton, with a wide range of clast sizes (Goldthwait, 1971). There are different types of till based on composition of source material, glacier type, depositional environment (marine vs. terrestrial), thermal regime of the glacier and depositional processes. The most common classification of tills is based on the process by which they were deposited. A glacier can deposit subglacial sediments in a variety of ways depending on the type of material, the topography, as well as the thermal regime of the glacier. A lodgement till is glacial debris that has been plastered on to the subglacial substrate when the friction between the underlying bed and the debris is greater than the force exerted on the debris from the glacial ice. The friction inhibits the debris from being transported further so it becomes deposited in the subglacial environment (Boulton, 1975, 1982; Dreimanis, 1989, Benn and Evans, 1998). Melt-out till is formed when material becomes frozen within the basal ice of a glacier. By some increase in temperature or a change in the freezing point of ice, due for instance to variations in geothermal heat, increased friction, or heat advection by water, melting releases the sediments from the basal ice and deposits them beneath the glacier (Benn and Evans, 1998). An ablation till is formed when an inactive and motionless glacier releases sediments due to melting. This process can occur both at the margin, and in the subglacial environment (Martini et al., 2001). Flow till forms when subglacial sediments become saturated with water. The saturated sediments can be released and behave as a debris flow

when they encounter a descending slope in topography (Martini et al., 2001). Deformation till, not to be confused with the deformable bed, is material that has been deposited as a group of layers. These layers deform together by processes other than simple shear, and act as a buffer between the glacier and an uneven surface beneath it (Martini et al., 2001).

There is some support to show that it is possible to identify the depositional processes in an ancient till using till pebble fabric analysis, or simply "pebble fabric" (e.g. Dowdeswell and Sharp, 1986). Pebble fabric analysis will be used to verify the depositional processes of the tills at Conrad's Head that have been previously interpreted (Nielsen, 1976; Stea and Pe-Piper, 1999).

2.1.1. The deformable bed

The deformable bed has been defined as a coupled relationship between a glacier and the unconsolidated sediments beneath it, which causes an increase in glacier velocity and/or a change in the surface slope of the glacier, as well as the deformation of the underlying sediments as a consolidated unit (Hart, 1995). In a deformable bed, the subglacial till deforms as a unit under the stress of overriding ice, as opposed to simply being deposited in discrete layers by the lodgement process.

According to Glenn's Flow law (Hooke, 1998) the horizontal velocity of ice is a function of the surface gradient of the glacier (i.e. flat ice will have no net horizontal velocity). There are three primary factors that control ice velocity under a given surface gradient (Fig. 2.1): (i) the deformation of internal ice; (ii) slip along the boundary between the basal ice and its underlying substrate; and (iii) deformation of the underlying substrate. The deformation of the substrate will ultimately generate a deformable bed. Under flow conditions where a

deformable bed does not exist, glacier ice velocity is mainly controlled by internal ice deformation (Fig2.1) The physical properties of the bed that underlies a glacier can greatly affect its dynamics. For instance, deformation of the bed observed under Ice Stream B (Murray, 1997) accommodates much of its rapid velocity and perhaps a surging behaviour (Murray, 1997) despite the low surface gradient of the ice. A deformable bed can therefore trigger the collapse of an ice sheet, or lead to excessive calving rates such as those witnessed during Heinrich Events (Dowdeswell et al., 1995). Drumlins have been proposed as areas of increased consolidation within the deformable bed (Hart, 1995) that resisted the surrounding subglacial erosion, so the founding till of a drumlin should preserve the consolidated remnants of a deformable bed.

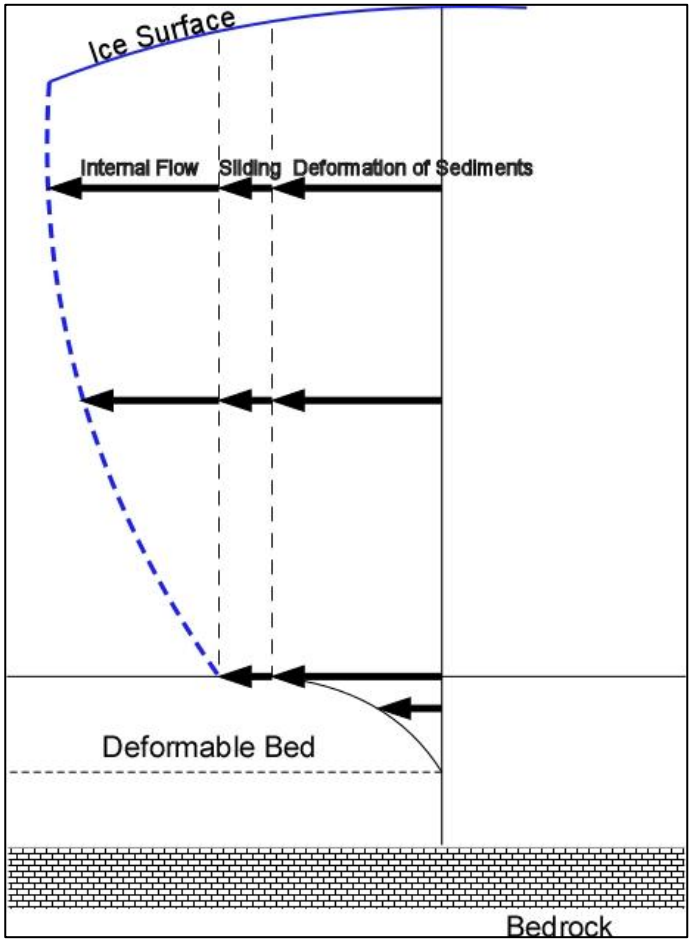

Figure 2.1: Schematic drawing showing the relationship between an ice sheet and the deformable bed. The black arrows indicate flow vectors of (i) internal deformation; (ii) basal slip; and (iii) deformation of sediments. After Alley, et al., 1986.

Subglacial beds have an immense effect on the deformation, deposition and erosion (Knight, 2010) that occurs beneath a glacier, which can effectively shape entire landscapes. Subglacial materials have a profound control on the long term stability of ice sheets (Murray, 1997). By understanding the behaviour of the material beneath a glacier, and in turn, a glacier's

longevity, a better understanding can be gained of glacial dynamics. Having knowledge of the deformation taking place under ancient ice sheets allows for reduced complexity when predicting additional velocities attributable to slip rates (Cuffey and Paterson, 2010) and improves our capacity to model ice sheets. This could have implications in estimation of ice sheet volumes over time, as volume is controlled by surface gradient which in turn is controlled by the presence and thickness of the deformable bed (Clark et al., 1996), and can even control atmospheric dynamics and climate change (Clark, 1993). It is also important to know the quantity of the material transported in the deformable bed (Alley, et al., 1997; Cuffey and Paterson, 2010). Knowledge of the quantity of material can have applications in the geoscience community, such as improvements in the understanding of glacial sediment transport in specific regions of interest to the mineral industry.

2.1.2 The deformable bed in ancient tills

As noted, recognizing the deformable bed in an ancient till can be challenging, due to the inability to observe the interaction between ice and subglacial sediments. Several techniques have been used in both modern and ancient tills to assess and quantify the presence of a deformable bed beneath a glacier.

Boulton and Jones (1979) reported their work on Breidamerkurjökull, a modern glacier in Iceland. There, they placed markers into a subglacial layer of unconsolidated sediments that were exposed due to an ice tunnel. Boulton and Jones drilled 35 markers to a depth of 90cm vertically into the sediment layer at regular intervals and left them for several days. They found that the markers closest to the surface experienced the most shear stress and moved a maximum of 50 cm away from their original horizontal position.

(Fig. 2.2) They demonstrated that the sediments beneath the glacier accounted for about 88% of the glacier movement.

Alley et al. (1986) employed geophysical methods to identify a deformable bed beneath Ice Stream B in Antarctica. Using seismic imaging, they were able to detect a 5-6 m thick, porous layer of unconsolidated sediments under the ice sheet. They then calculated the velocities of the ice and the shear stress of the sediments and determined that the basal ice velocity was largely attributed to the deformation of the sediments beneath the ice sheet.

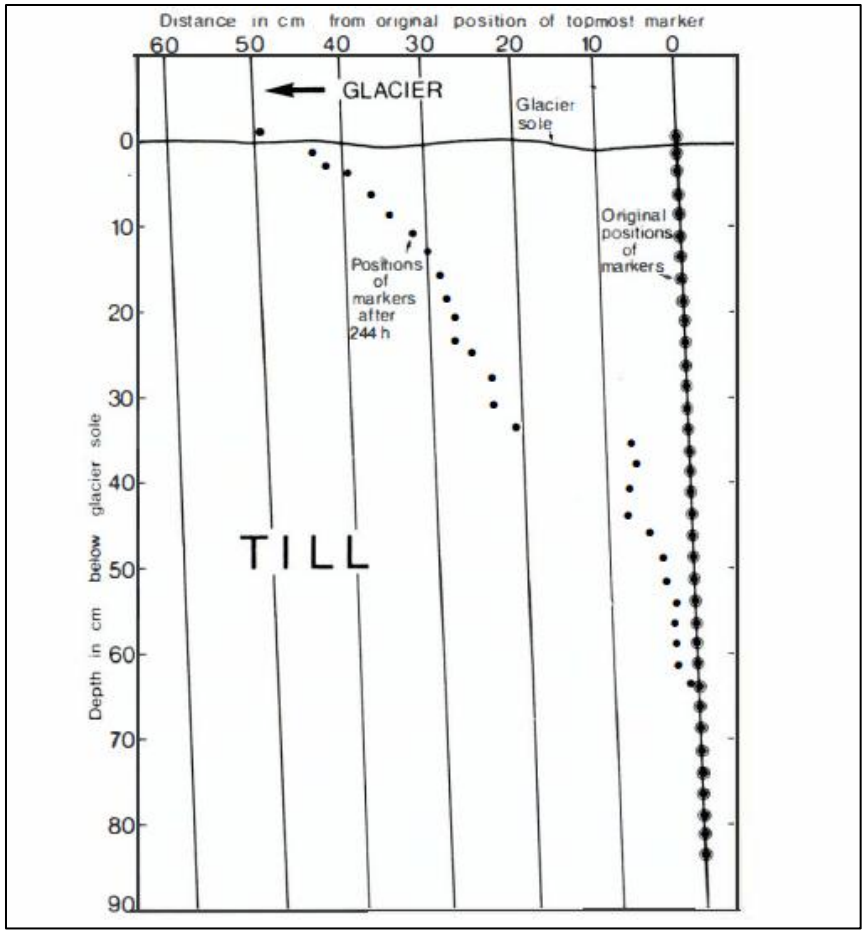

Figure 2.2: Displacement of a series of markers inserted in till beneath BreiIJamerkurjokull in Iceland. The markers were drilled in from an englacial tunnel and dug out after 244 h. 88% of the forward movement of the glacier at this point occurs through deformation of the substratum. From Boulton and Jones, 1979.

However, while a deformable bed has been observed in modern glacial environments, it has been difficult to document its presence (especially thickness) in previously deposited tills. Iverson et al. (1998) used a ring shear apparatus to quantify strain that occurred among natural tills of different clay content. Iverson's work has application to this project:

tills with higher clay content are weaker than a coarse-grained till when exposed to shear stress which simulates the presence of a glacier overlying the sediments.

Menzies et al. (1997) observed microsedimentary structures in a drumlin field in New York. The researchers took several samples from different areas of several drumlins that displayed complex stratigraphy and showed evidence of deformation. By observing microstructures in the field and in thin section, they found evidence that the till had been deformed in a direction parallel to the local paleo-ice flow direction. They were also able to distinguish between brittle and ductile deformation in different drumlin sections. Ductile deformation microstructures included folds, strain shadows and rotations. Brittle deformation microstructures were observed as shear planes, faults and kink bands.

The aim of this thesis is to investigate a new method to distinguish a deformable bed in an ancient till. By measuring the concentrations of a cosmogenic isotope in quartz sand from multiple samples collected in a vertical transect through a till, it may be possible to use the concentration vs. depth pattern to infer the presence of a deformable bed within a till. If the test is successful, the technique may be applicable to other ancient till settings where knowledge of the presence and thickness of a deformable bed is sought for understanding ice sheet dynamics.

2.2 Glacial Geology of Conrad's Head

2.2.1 Brief glacial history

From about 75 ka to 12 ka, Atlantic Canada was enveloped by a collection of ice divides known as Appalachian Glacier Complex (AGC) during a period known as the Wisconsinan glacial period (Stea, 2004, 2011). Prior to this, there was a prolonged interglacial (i.e. the

OIS 5 interglaciation from 135 to 75 ka). While there is sufficient evidence to indicate that no ice covered Nova Scotia during OIS 5, the interglacial between glaciations associated with OIS 4 (~75 to 55 ka) and OIS 2 (~30 to 16 ka) was shorter and apparently colder. Thus, beyond the ~50 ka limits of radiocarbon dating, the chronology for Nova Scotia's glacial history is poorly constrained and largely based on the conceptual model of the AGC. The AGC represents a median between a maximum and minimum model based on correlations between terrestrial and marine tills. The maximum model assumes that Atlantic Canada was covered by continental ice sheets, while the minimum model suggests that local ice centers were the source of glaciation in the Maritimes (Stea et al., 1998).

The Wisconsinan has been divided into five major stages of glaciation (Fig 2.3) based on glacial landforms, striations, pebble fabric and ice sheet modeling. The oldest of these stages is the Caledonia Phase (Phase 1). This period has been defined by a south-eastern flow direction based on pebble fabric and striation orientations. During the Caledonia Phase, highland areas across eastern Canada were eroded to form glacial deposits. The source of the ice sheet in Nova Scotia has been a topic of debate. Recently it has been determined that the ice sheet likely originated from a local source in central New Brunswick, as opposed to extending from the Laurentide Ice Sheet (LIS) that covered the rest of Canada during the most recent glacial period. Evidence against the Laurentide Source stems from a lack of Laurentide erratics found in tills across Nova Scotia or even PEI. There is also no evidence of south-eastern flow between Quebec and New Brunswick. This would indicate a local ice center located in New Brunswick that would have prevented the LIS from extending into Nova Scotia. The mature tills deposited during the Caledonia Phase are significantly thicker than younger tills and also contain a far travelled erratic

component. North Mountain Basalt erratics have been found in till deposits on Sable Island, providing evidence that the ice sheet likely extended to the Scotian Shelf. The Caledonia tills are laterally continuous across all of Nova Scotia and have been correlated with OIS 4-3. The first Wisconsinan till sheet lies directly on the interglacial (OIS 5) organic beds and can also be observed overlying varved glacial lake sediments and interglacial organic lake sediments in lowland regions (Stea, 2011). Following the Caledonia Phase, there was an ice retreat from coastal Nova Scotia that lead to a short interglacial between ~50-25 ka. It was following this retreat that the ice center migrated closer to PEI and merged with the Laurentian Channel ice stream. This marked the beginning of the Escuminac Phase (Phase 2), during which time the Lawrencetown Till was deposited. The Escuminac Phase lasted from ~25-20 ka. Tills deposited during this time contain a higher erratic content than observed in earlier deposition, possibly due to rapid flow from ice streams inhibiting basal mixing (Stea, 2011). Escuminac Phase deposits on the Scotian Shelf have been correlated with terrestrial deposits, indicating that both the Caledonia and Escuminac phases extended to the shelf. This glaciation was followed by the Scotian Phase (Phase 3) (~20-17 ka), in which the Scotian Ice Divide was formed by a large ice stream. The ice stream caused the glacier to flow northwest towards the Bay of Fundy and southeast towards the Atlantic coast (Stea, 2004). It was during the Scotian phase that the upper Lawrencetown till was reworked to form a thin hybrid till (Stea, 2004). Following the Scotian phase, ice began to retreat from the continental margin. The Chignecto Phase and the Collins Pond Phase (~15.9-11.7 ka) were the final two stages of glaciation but neither extended to the coastline of southern Nova Scotia, therefore glacial deposits are not visible at the Conrad's Head study area.


WM-MH
Northumberland Phase-(~200 ka)
ND
LIS
LIS?
LIS?
?
Caledonia Phase (75–64 ka)
ESC?
Mid Wisconsinan (64–25 ka)
LIS
ESC
?
Escuminac Phase (24–20 ka)
LIS
Cape Breton Channel Ice stream
Scotian Phase (20–17 ka)
LIS
Chaleur Bay Ice Stream
C-NM
Cape Breton Trough Ice Stream
Laurentian Moraine
SID
SID
Scotian Shelf End Moraine Complex
Scotian Phase (20–17 ka)

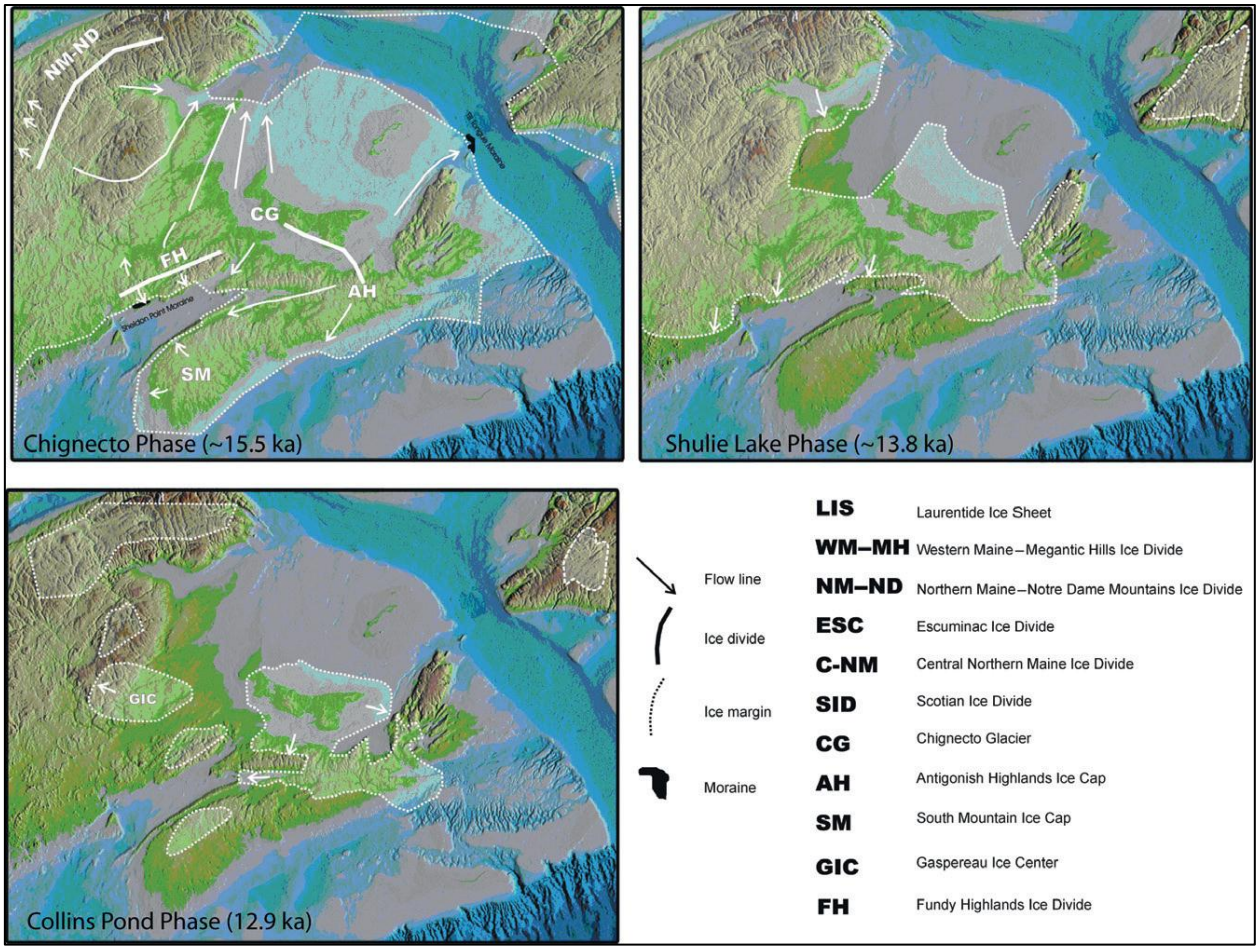

Figure 2.3: Evolution of the Appalachian Glacier Complex from the Illinoian (MIS 6) to the Late Wisconsinan in (MIS 2) in Maritime Canada. The location of hypothetical ice centres and divides, and flow lines are shown. The extent of the glacio-isostatic Goldthwait and DeGeer Seas are not defined. Flow data is largely derived from striae and landform compilations by Prest (1973), Rampton et al. (1984), Seaman (1989), Stea et al. (1992a) and Grant (1994). From Stea et al., 2011.

2.2.2 Regional and local glacial stratigraphy

Complete stratigraphic records of glacial history are lacking in eastern Canada before OIS 6 (Stea et al. 2011) (Fig. 2.4). The oldest Wisconsinan glacial till bed across Nova Scotia are typically the grey lodgement tills (Nielsen, 1976), of which the Hartlen till is an example. These tills are typically overlain by either red lodgement or melt-out till. In some regions, this is overlain by an ablation till, but this is not seen in the Conrad's Head section. A hybrid till can also be observed in areas such as Whites Lake (Nielsen, 1976). It is referred to as a hybrid due to its complex history in the subglacial environment. The Caledonia Phase and Escuminac Phase till sections are significantly thicker than till deposited in later phases and are separated by fine and coarse grained glaciomarine or lacustrine sections in some localities, with finer grained sediments occurring predominantly in Cape Breton and central mainland Nova Scotia, and with southern Nova Scotia dominated by coarser grained material (Stea, 2004). The Scotian Phase tills are less than half the thickness of the Escuminac Phase till deposits and are continuous and widespread across Nova Scotia. The Collins Pond age glacial tills (Late Wisconsinan) only encompass a 2 ka timespan and are not laterally continuous in southern Nova Scotian sections. The OIS 5 Sangamonian-age (135-75 ka) interglacial period material underlies all the Wisconisnan age tills, and is defined by the presence of forest material and organics (Stea, 2004).

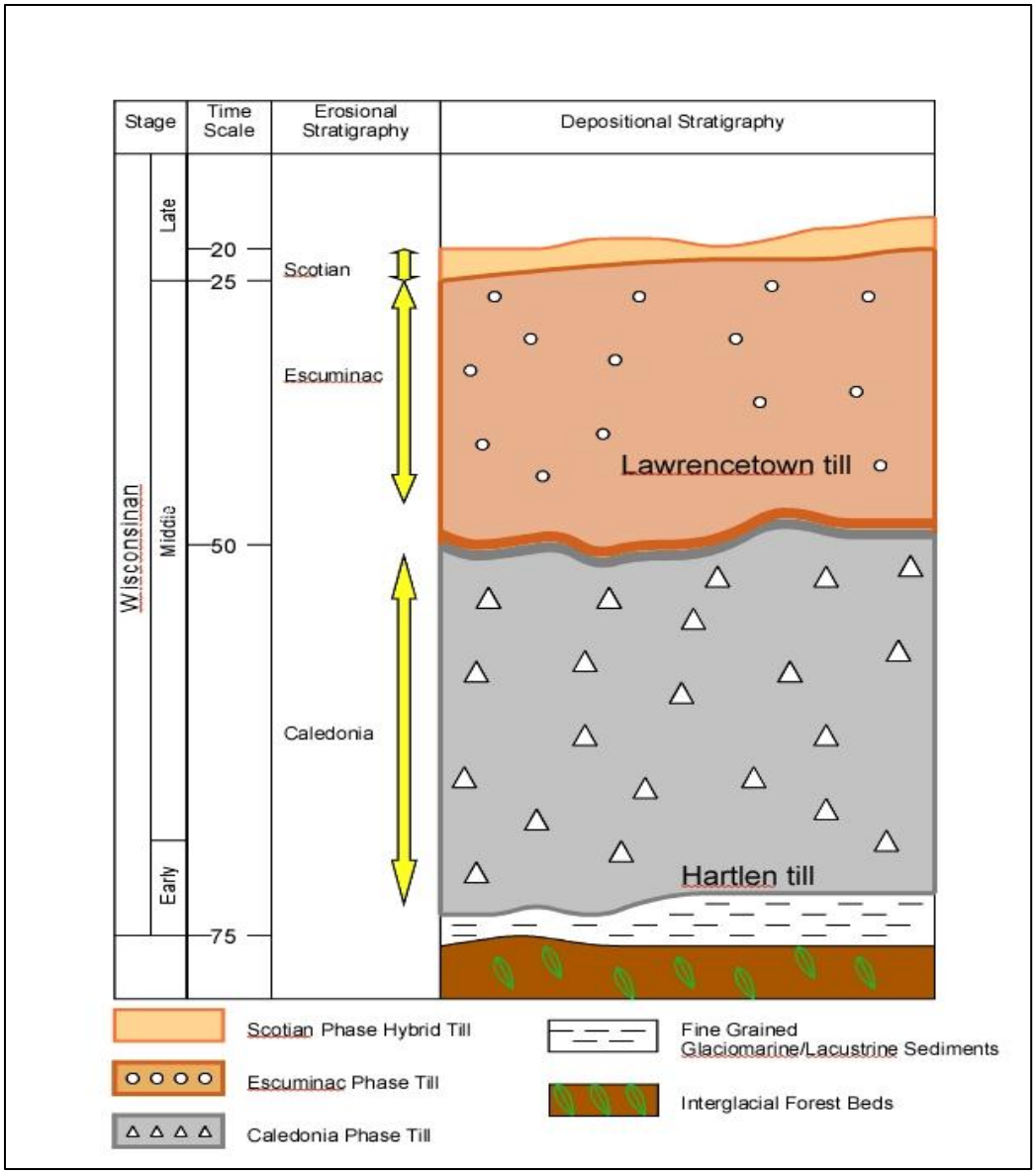

Figure 2.4: Stratigraphy of central Nova Scotian glacial deposits showing major till deposits from the Caledonia to Scotian phases of glaciation. After Stea et al., 2011.

2.2.3 Geochronology limitations

The Hartlen Till has yet to be dated using geochronological methods, but is thought to be of early to mid-Wisconsinan origin (King, 1996) based on correlation with marine till deposits and field relation to other sections that have been bracketed between radiocarbon dating and U/Th dates (Stea et al. 2011). The problem with using these techniques in the

Hartlen Till region is that both require sources of organics or shell material. ^{14}C has a half-life of 5730 years, and therefore works best on recent deposits less than 50 ka (Dickin, 2005). U/Th can be used to date much older samples, up to about 500 ka (Dickin, 2005). Both of these methods also require knowledge of the context in which the organics or shell material was deposited. Cosmogenic nuclide dating is also used for determining the age of till that is buried by other tills or sediment (Balco and Rovey, 2008). As dating these till are such an arduous task with numerous variables, it has seldom been completed on pre-Scotia Phase tills onshore. Stea et al., (2011) have compiled a list of till sections that were able to be dated from across Nova Scotia representing type sections from various glacial periods, allowing us to begin to establish a more accurate Atlantic glacial history as more data are uncovered.

2.2.4 Till stone lines

Just centimeters above the boundary of the Hartlen and Lawrencetown tills, a continuous (dozens of m) line of large (0.5-2 m) boulders seem to separate the two distinct tills. Another identical line lies about 2-3m above the one at the contact. It is not clear as to how these boulders came to be placed here, but several possibilities exist. The first hypothesis is that these boulders are remnants of an interglacial period that would have occurred after the Hartlen Till was deposited and before the Lawrencetown Till was deposited, i.e. during OIS 3. If an interglacial period did, in fact, occur, then an increase in ^{10}Be concentrations would be visible in the curve constructed from the sample data. This increase would be caused by the extended exposure of the sediments, enabling the production of more ^{10}Be after the glacier had retreated. The sediments beneath them

would have significantly lower concentrations of ^{10}Be due to the attenuation length of the secondary cosmic rays. An interglacial period could be possible, because as seen in a stratigraphic column produced by Stea (2004), there is a period in which 'interglacial forest beds' appear between the Caledonia Phase and the Escuminac Phase in Cape Breton, meaning that an interglacial period may have extended to modern-day Lawrencetown.

Another hypothesis comes from Hart (1998), who described a similar phenomenon to a stone line which she refers to the stone line as a subglacial boulder pavement. The boulder pavement has been shown to be a characterizing feature within a deformable bed, and is interpreted by Hart to result from a subglacial erosional lag. As finer grained materials get eroded and transported within the deforming bed, the larger boulders take more time to erode and move. As they once occurred in a flow of poorly sorted material, the result is that they eventually form a continuous lateral line and can be found along the same plane (Fig. 2.5).

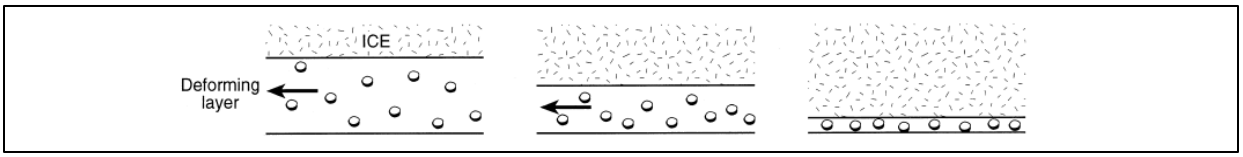

Figure 2.5: Schematic diagram to show the formation of boulder pavements within the subglacial deforming layer associated with an erosional lag. From Hart, 1998.

Older studies (Clark, 1991) hypothesized that the deformable bed had similarities in behaviour to a debris flow, and that large clasts would sink to the bottom of the flow, allowing for the formation of boulder pavement. But Hart suggests that a lack of vertical striations on the sides of boulders is indicative of a lack of vertical motion within the flow. The presence of striations which were observed by the author to be principally on the top and bottom of boulders in the stone lines at the Conrad's Head till section, suggests that these large clasts were transported horizontally in the ice flow direction parallel to the

pebble fabric. Boulder pavement could be evidence for a deformable bed at the base of the Lawrencetown Till. However, no stone lines were observed within the Hartlen Till matrix.

2.3 The cosmogenic nuclide tracer approach

The aim of this thesis is to test two related hypotheses. The first is that the Hartlen Till, which follows a prolonged interglacial, will have quartz that contains a much higher concentration of ^{10}Be than the overlying Lawrencetown Till which would have eroded substrates that were exposed for a shorter time. This test will help support the current chrono-stratigraphic interpretation of the glacial history of Nova Scotia by Stea and others. The second hypothesis is that the pattern of ^{10}Be concentration through the Hartlen Till will help define the presence of, and if suitable patterns occur, the thickness of, a deformable bed in an ancient till. To accomplish these tests, we will use ^{10}Be in quartz as a tracer for the targeted process.

The use of cosmogenic isotopes to determine landscape history and surface process rates is increasing due to their versatility in terms of compatible material and wide range of decay rates, which provide an applicable age range from 10^1 to $>10^6$ years (Gosse, 2012). Cosmogenic nuclides are produced by the interaction of primary and secondary cosmic-ray particles with atomic nuclei in a wide variety of materials (Lal, 1991). Cosmic rays (high-energy, charged particles) originate mainly from supernova explosions that occur outside of our solar system. These rays travel into our solar system, and when they reach Earth and interact with our atmosphere they produce secondary cosmic rays (Lal, 1991). The secondary rays then collide with atomic nuclei within materials such as water or minerals

and produce new isotopes. In the case of ^{10}Be, the cosmogenic isotope of interest in this study, a spallation reaction between the secondary rays and Si and O within quartz produces the isotope. Spallation occurs when a high-energy nucleon collides with the nucleus of Si and O, and shatters the target nucleus into many pieces with lighter masses, including nuclides and sub-atomic particles (Lal, 1991). The quartz grain retains a signature of the reaction, and if sufficiently large, the concentration of the in situ produced ^{10}Be can be determined using accelerator mass spectrometry (AMS). Quartz is an ideal mineral for measuring these concentrations due to the fact that it has a simple chemical formula that does not involve solid solutions, making the production rate of ^{10}Be in SiO_2 less complicated to determine. Additionally, its resistance to chemical weathering and abundance in the Hartlen Till make it the obvious mineral of choice. ^{10}Be concentrations can be used to determine how long the material was exposed to secondary cosmic rays without being obstructed by some sort of shielding, which in the case of this study could be an ice sheet. It can also be used to determine how long material has been buried (Balco and Rovey, 2008) measuring erosion rates (Willenbring and von Blankenburg, 2010), and as a tracer for geologic process (Staiger et al., 2006). Repka et al. (1997) performed vertical TCN profiles to date stream terraces in Utah due to the complex depositional history of the fluvial system, and the vertical depth profile method to date alluvium has evolved with improvements in accounting for error and factors that control the concentrations (Hidy et al. 2010).

The idea to use the tracer approach for this project originated from a paper by Staiger et al. (2006). This was the first study to use an in situ ^{10}Be tracer. Their purpose was to classify cold-based and warm-based tills using the concentration of in situ ^{10}Be in till on

Baffin Island. For the present study, it was hypothesized that the combination of a vertical depth profile strategy with a tracer approach could be used to establish if a deformable bed existed. Thus, the primary purpose is not to date the till, but to determine the pattern in the inherited concentration of ^{10}Be in the quartz grains produced in situ from exposure prior to their subglacial erosion, transportation and deposition as till. Considering the hypothesis posed by Hall and Mignon (2010) that net erosion beneath a glacier decreases as the distance from the margin decreases, we considered the option of attempting a study of the lateral variation in inheritance in a single till unit. However, this would involve several obstacles, such as difficulty in accessing samples, the requirement of a significant number of measurements (more than the 8 used in the present experiment), and overcoming other cosmogenic nuclide-related problems. For this thesis research, only the vertical change in concentration (not lateral) will be studied. This new TCN approach may provide a means (safer and cheaper than experiments under a modern glacial system and applicable in many different glacial environments) to determine the presence of, if not average thickness of, a paleo-deformable bed.

3.0 Methodology

3.1 Study Site Selection

The Conrad's Head till section was selected as the site for this project for several reasons. First, the area has been well studied by E. Nielsen in his PhD thesis, as well as by R. Stea (1994, 1996, and 2004), and personal communications with Stea have helped determine the ideal study area. Also, the Conrad's Head section is an exceptional cross-section of a drumlin, cut approximately perpendicular to its long axis, which enabled a representative till fabric to be taken of the Hartlen Till that formed the drumlin (Stea, 2004). The sampling site that was chosen is located at the center of the drumlin cross-section, the area at which its height is greatest. This allowed for greater spacing between the vertical samples to give us a more representative data set.

The Hartlen Till was an ideal glacial deposit to study the effects of the deformable bed. This is because the till is laterally continuous across the province and is the thickest till deposit. The study completed at Conrad's Head can therefore be applied to other early Wisconsinan tills in Nova Scotia. Not only is it laterally continuous, but it is the one of the oldest tills on land, and marks the beginning of the Wisconsinan glacial phase after the OIS 5 interglacial period (Stea, 2004). This allows us to observe significant amounts of ^{10}Be in the deposit due to the extended exposure to secondary cosmic rays. Finally, the Hartlen Till is homogeneous in not only composition, but grain size, based on field observations. From this, we can infer that if a deformable bed was present, it formed in one or two thick layers, rather than multiple thin, discreet deposits. (Fig. 3.1).

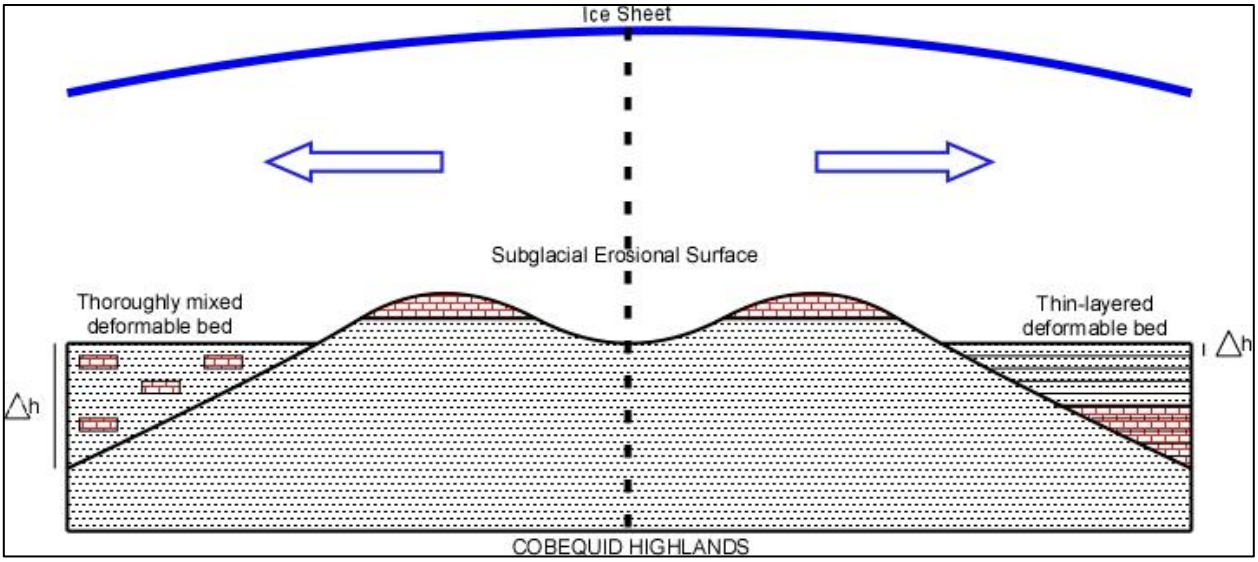

Figure 3.1: Schematic drawing showing till deposition with a thick and thin deformable bed. The stratigraphic section on the right shows mixing of the two rock types, while the section on the left shows progressive deposition in thin layers.

3.2 Field methodology

3.2.1 Pebble fabric

Before TCN sampling could commence, some field work was deemed necessary to build on the thorough work by others on the tills at and in the vicinity of Conrad's Head. In particular, it was important to evaluate the classification of the till type, and to check that the sediment to be sampled was representative of the Hartlen and Lawrencetown till found in the vicinity. Previous work by others (Stea, 2004; Nielsen, 1976) suggested that the Hartlen Till was formed by lodgement processes. To verify this, a till fabric was taken from the Hartlen Till, which due to the paucity of suitable clasts and compaction of the till, required several trips to Conrad's Head (Appendix A). The preliminary step was to take till fabric data from both the Lawrencetown and Hartlen tills. Two 1 m x 1 m caves were dug

into the near-vertical coastal section using shovels and pick-axes in the lower till (Hartlen Till). The holes were approximately 20-30 cm into the cliff to avoid the effects of remobilization of the clasts due to recent slope processes. 50 prolate clasts, 25 from each site, with axial ratios of 2:1 or higher, were then removed from the till and a non-magnetic knitting needle was inserted into the till, in the same orientation of the long axis of the clast, to verify the stone axial ratio. The trend and plunge were determined using a Silva compass with an inclinometer, and the orientation of the long axis was recorded, as well as the lengths in the a, b and c axial directions, and the rock type. After the till fabric measurements were completed, the data were input into a program (Stereonet-7, Allmendinger et al., in press) that created a stereonet projection (Fig 4.1) of the data and provided a statistical analysis of the results which included eigenvalues. The S_1 eigenvalue is useful to help characterize the types of till (Dowdeswell and Sharp, 1986) because different till depositional processes (meltout, lodgement, flow, etc.) will yield characteristic ranges of fabric strength (Fig. 3.2). For instance, meltout tills usually have the highest fabric because clasts align in ice more uniformly than a lodgement process within a till comprising a mixture of clasts and matrix. The Dowdeswell and Sharp classification is based on tills that are diamictons, i.e. there is a significant clast content and the clasts have a large range of clast sizes. The directional data were also compared with previous till fabric and ice flow measurements (Stea, 1996) on the Hartlen Till. If the till is found to have been deposited or deformed by some process other than lodgement (i.e. flow till deposition or post-depositional deformation) then the Hartlen Till, or this locality, should not be used for the TCN sampling.

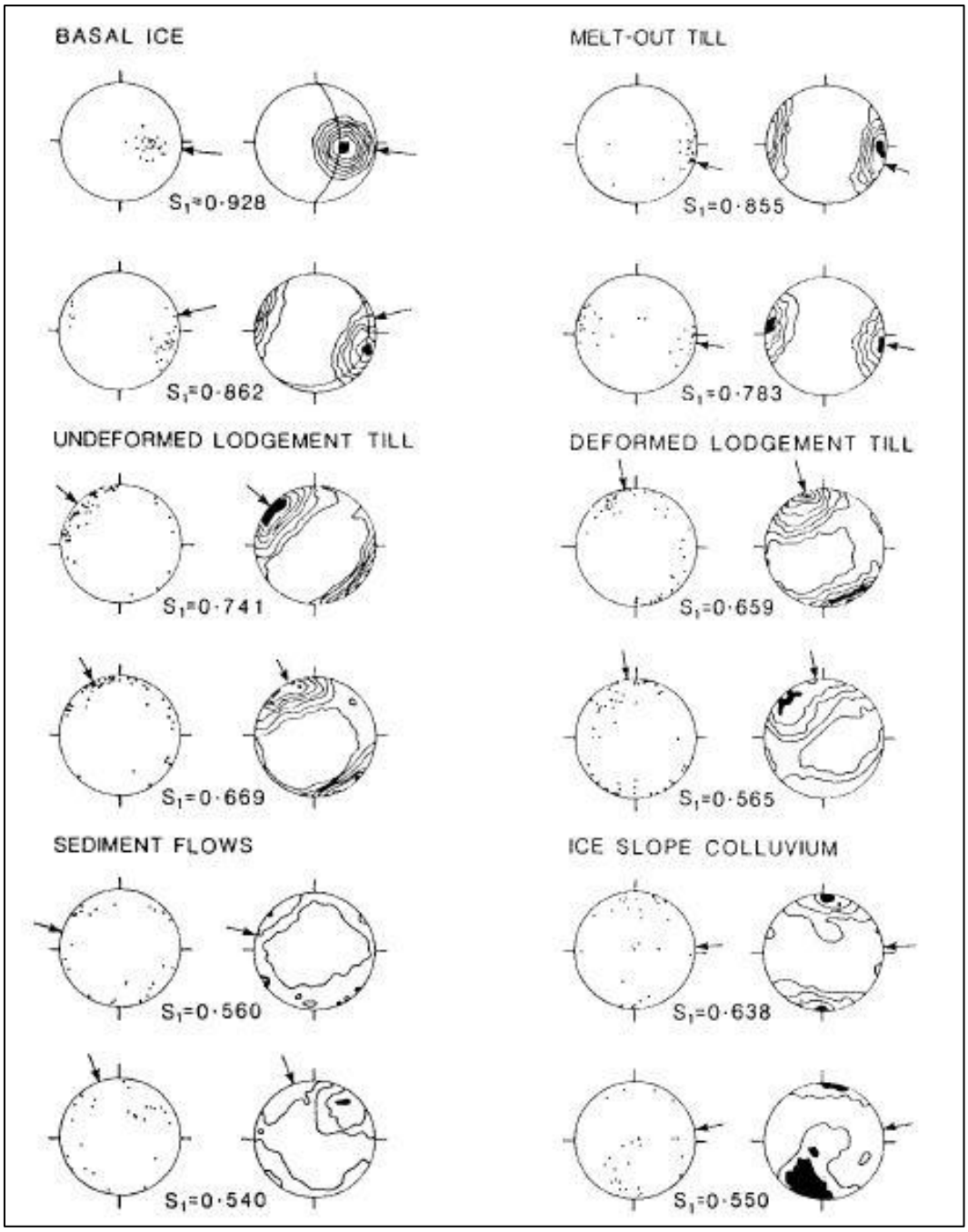

Figure 3.2: Point and contoured diagrams of pebble fabric data from basal glacier ice and several glacial sedimentary facies, plotted on Schmidt equal-area projections. Data for basal ice, melt-out till, sediment flows and ice slope colluvium are from Lawson (1979a, b). Arrows indicate the observed direction of ice or sediment flow. The contour interval is two standard deviations (Kamb, 1959). From Dowdeswell and Sharp, 1986.

3.2.2 Grain size

Gross estimates of grain size were also used to determine if the till was completely homogenized, or if there was some vertical trend in grain size that would suggest that the entire till was not mixed. Non-homogeneity is a favourable condition because it would suggest that the deformable bed at any time was of less thickness than the entire till unit. During another visit to the study area, three small samples were taken for grain size analysis near the contact between the Lawrencetown and Hartlen tills. One sample was taken about 5 cm beneath the contact, within the Hartlen Till, another was taken 2 cm above the contact, within the Lawrencetown Till, and the third was taken 20 cm above the contact, again in the Lawrencetown Till. These were taken to observe potential changes in grain size within the Hartlen Till, as the preliminary grain size analyses suggested that the Hartlen Till fined upward. The two samples in the Lawrencetown Till were taken for comparison purposes but may be useful to determine if a similar trend was visible in the Lawrencetown Till or if there is any mixing between the two tills at the contact. The grain size analysis was also useful to ensure that the fine grained Hartlen till had sufficient coarse quartz for the TCN measurements.

3.2.3 TCN Sampling

Eight samples were taken vertically from the Conrad's Head till section, six from the Hartlen Till and two from the Lawrencetown Till. Each sample site was approximately 40-50 cm in width and about 15 cm in height (Fig. 5.2). The vertical spacing between each hole was approximately 60-80 cm, which was deemed sufficient for a pilot study to test of the

^{10}Be tracer method could be useful for determining the presence of a deformable bed. The samples spanned the entire upper 5 m of the Hartlen Till exposed above beach level. Sufficient surface material was removed to ensure that samples were collected deeper than the effects of the thin colluvial cover, which was readily identified by being less consolidated and by colour. Care was taken to prevent contamination of each sample by collapse of the hole, by material from above falling into the sample bag, and by cleaning the sampling tools. Due to the high level of compaction of the Hartlen Till, a hammer, knife, and pick were used to break small clumps of the sediment out of the hole, and then a garden shovel was used to transfer the sediment to a gallon-size heavy duty Ziplock bag. The upper five samples were collected while standing on a 24-foot aluminum ladder. Each sample was triple-labelled and double bagged. Because the rate of erosion was considered sufficiently high (see discussion), the negligible influence of in-situ production of ^{10}Be on the exposed sea cliff section was not considered during sampling.

3.3 Analytical Methods

Physical and chemical pre-treatment and isotope geochemistry was conducted on all 8 samples in order to prepare BeO targets for analysis at the Purdue Rare Isotope Measurement (PRIME) Laboratory at Purdue University in Indiana.

3.3.1 Physical preparation of samples

The eight samples from the Conrad's Head till section were prepared for acid treatments. The first step was to clean the samples of the fine clay by means of wet sieving. The samples were placed in a 150 μm sieve and run under hot water for several minutes, to

ensure that the fine-grained material was removed from the samples. They were then dried in an oven at a temperature of about 80 °C. The dried samples were then sieved again and separated into four bags per sample site (>350 μm, 250-350 μm, 150-250 μm and <150 μm). From a chemical point of view, the best results would come from the coarser 250-350 μm sand because the lower surface area to volume proportion of each grain reduces the rate of dissolution.

However, some samples did not contain enough coarse quartz for optimal results. The 150-250 μm sand was then used in its place. Due to the higher ratio of surface area to volume, the HF acid treatment to dissolve unwanted minerals was limited to the removal of enough quartz to ensure that any meteoric ^{10}Be adhered to the quartz surface (and surface of microfractures) was removed. This meant that non-quartz phases needed to be separated by a Franz Magnetic Barrier Separator (available in the Fission Track Lab of the Dalhousie Geochronology Centre (DGC). The Franz creates a magnetic field in which the fine-grained till particles pass through along a chute. At predetermined currents, the electromagnet separates ferromagnetic (eg. magnetite, hematite) or paramagnetic (e.g. feldspar) minerals. Quartz is diamagnetic and is repelled by the magnetic field and therefore reasonably well-isolated from the other phases.

3.3.2 Chemical pre-treatment

Additional quartz purification took place in the DGC Cosmogenic Nuclide Exposure dating Facility (CNEF). Chemical preparation involved dissolution of any remaining unwanted minerals. The CNEF's process is based on that of Kohl and Nishiizumi's (1992), which requires some of the quartz samples to be dissolved with acids (about 30%) in order to remove the meteoric ^{10}Be.

The samples were first treated with Aqua Regia, a mixture of 3:1 HCl and HNO_3. Concentrated (2:1) HF acid to water was used to help dissolve remaining minerals, leaving quartz behind. The final step to obtain quartz concentrates used approximately 30 g of the samples in multiple 4 L HDPE bottles. Approximately 80 g of HF and 30 g of HNO_3 acids in 3.5 L of Type 1 water were placed in 25 gallon ultrasonic tanks. To verify quartz purity, a semi-quantitative measurement of Al in the 1 g of quartz was obtained with Quant-EM Aluminum sticks. Samples with less than 100 ppm Al were considered sufficiently pure for the experiment (the same standard is widely used for ^{10}Be dating experiments).

To produce the BeO targets, CNEF lab manager G. Yang conducted the required chemistry and target packing procedure. A predetermined concentration of ^{9}Be was added gravimetrically (as $BeCl_3$ (aq)) with known Be concentration and density) to each of the 8 samples, and to one empty digestion vessel that would serve as a process blank. All labware was either virgin disposable plastics, or carefully acid washed teflonware. A series of steps including ion chromatography with column chemistry and precipitations at controlled pH with ammonium hydroxide was used to extract the Be (^{10} Be and ^{9} Be) from the solution. The Be was precipitated with ultrapure ammonia gas. It was ignited in a quartz crucible Bunsen burner flame to produce BeO, which was mixed with niobium powder and sent to PRIME Lab at Purdue University for AMS analysis of the $^{10}Be/^{9}Be$ (see Appendix B for more details of the target chemistry procedure).

The AMS data and chemical data were reduced, concentrations were calculated, and the blank correction was made. The propagation of the random error included the principal sources of error: AMS precision and the uncertainty in the Be concentration in the carrier.

4.0 Results

4.1 Grain size

Based on the grain size analysis of one of the Hartlen Till samples using both wet and dry sieving, it was determined that the majority (~53%) of the Hartlen Till was made up of granules and cobbles (grains >350µm) (Table 4.1). The matrix of the diamicton is mostly silt and clay-rich (<150 µm) with some fine and coarse-grained sand components. Predicting that the concentrations of ^{10}Be in the sand fraction would be low, it was decided that equal fractions from both sand components would be used for the ^{10}Be isotope geochemistry to ensure a sufficiently high $^{10}Be/^{9}Be$.

Table 4.1: Grain size fractions from a sample taken within the Hartlen Till.

Grain Size	Beaker+Sedimen	Beaker	Sed Mass	Total Mass	Fraction	Sieve Sizes
	g	g	g	g	%	
granules and pebbles	443.9	402.8	41.1	78.2	**53%**	>350 µm
coarse sand	385	379	6		**8%**	250-350
fine sand	393.1	382	11.1		**14%**	150-250
silt and clay			20		**26%**	<150 µm

4.2 Pebble Fabric

The analysis of the pebble fabric using Stereonet reveals a tight cluster with the principal axis dipping shallowly toward the northwest (Fig. 4.1). This orientation is consistent with the inferred ice flow direction determined by Stea (2004) for the Hartlen Till, and therefore provides assurance that the pebble orientations were not disturbed by post-depositional processes (although we cannot rule out inclination shallowing during subsequent glaciations). The two sites in the Hartlen Till which straddled the TCN sample site had principal eigenvalues of 8.718 and 8.518, so we assume an S_1 of 8.6 characterizes the Hartlen Till at Conrad's Head. No fabric analysis was completed for the Lawrencetown Till.

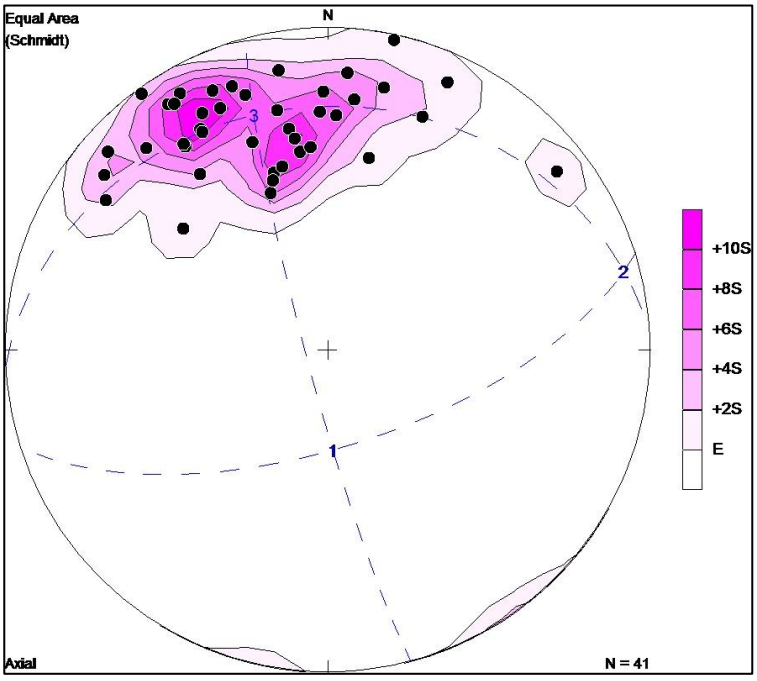

Figure 4.1: Stereographic projection of the pebble fabric data taken from the Hartlen Till at Conrad's Head, Nova Scotia.

4.3 TCN

The $^{10}Be/^{9}Be$ of the 8 samples was in the low 10^{-13} range with 1σ precisions ranging from 2.7 to 7.2% (Table 4.2). The process blank $^{10}Be/^{9}Be$ (1.8×10^{-14}) was significantly elevated above the average ($\sim 4 \times 10^{-15}$) for a carrier made from shielded beryl, but this has been observed in other experiments using large quartz masses (~90g) that require high volumes of hydrofluoric and other acids for dissolution. While the measured blank-corrected ^{10}Be concentrations (C_m) in the Hartlen Till ranged from 6.43×10^4 atoms/g to 8.31×10^4 atoms/g, the two Lawrencetown Till samples both had lower concentrations of approximately 1.50×10^4 atoms/g. Total analytical precisions, with AMS and other error sources added in quadrature, of the calculated concentrations ranged from 3 to 8% (Appendix C&E)

Table 4.2: Summary of AMS data and calculated post-depositional production (Cpd), inherited concentration (Cinh), and initial concentration (Ci). Complete data available in Appendix E.

Sample ID	Sediment Type	Depth	Sample Thickness	$^{10}Be/^{9}Be$ ratio (blank corrected)			Measured 10Be concentration			Post-depositional production	Inherited concentration	Initial concentration	
		(m)	(cm)	Measured Ratio	AMS precision (1s)		Cm	Total precision (2s)		Cpd	Cinh	Ci	Total precision (2s)
				10Be/9Be	10Be/9Be	fractional error	atoms/g	atoms/s	fractional error	atoms/g	atoms/g	atoms/g	atoms/g
LAW-08	Lawrencetown Till	-9.89	21	1.29E-13	6.00E-15	0.047	1.48E+04	1.50E+03	0.10	42	1.47E+04	1.52E+04	1.54E+03
LAW-07	Lawrencetown Till	-10.55	18	1.45E-13	7.00E-15	0.048	1.64E+04	1.71E+03	0.10	42	1.63E+04	1.69E+04	1.77E+03
HAR-06	Hartlen Till	-11.18	14	5.20E-13	3.00E-14	0.058	7.59E+04	9.26E+03	0.12	42	7.58E+04	7.83E+04	9.56E+03
HAR-05	Hartlen Till	-11.7	17	5.89E-13	2.70E-14	0.046	7.51E+04	7.52E+03	0.10	42	7.51E+04	7.74E+04	7.75E+03
HAR-04	Hartlen Till	-12.5	14	6.41E-13	2.10E-14	0.033	8.32E+04	3.19E+03	0.04	42	8.31E+04	8.58E+04	3.29E+03
HAR-03	Hartlen Till	-13.3	12	5.72E-13	2.00E-14	0.035	7.12E+04	5.74E+03	0.08	42	7.11E+04	7.34E+04	5.92E+03
HAR-02	Hartlen Till	-14.1	13	4.77E-13	1.30E-14	0.027	6.43E+04	4.34E+03	0.07	42	6.43E+04	6.63E+04	4.47E+03
HAR-01	Hartlen Till	-14.9	13	5.11E-13	4.00E-14	0.078	6.65E+04	1.09E+04	0.16	42	6.65E+04	6.86E+04	1.12E+04

5.0 Discussion

5.1 Classification as a lodgement till

The Hartlen Till has been classified by both Nielsen and Stea (1976, 2004) as a lodgement till. However, the high S_1 eigenvalues obtained from the stereonet projection (Fig 4.1) align more closely with a melt-out till deposition according to the classification system from Dowdeswell and Sharp (1986). Had the Hartlen Till been deposited in a melt-out process, there would be no deformable bed present. Melt-out tills are characterised by the release of sediments from the basal ice rather than experiencing coupled movement with the ice sheet. Nielsen compiled a list of characteristics common to lodgement tills which included: (i) high proportion of silt and clay; (ii) fissile structure where clay-rich; (iii) round and striated clasts; (iv) high level of compaction; (v) long-axis of clasts oriented parallel to flow direction; (vi) cobble sized clasts; (vii) a local sediment source; (viii) possible foliations present; (ix) narrow lenses of stratified sand may be present (Nielsen, 1976). The Hartlen Till displays all of these traits, except for the sandy lenses and foliations, which have been reported in some instances but are not essential for lodgement classification. In fact, more than 40% of the till stones in the Hartlen Till were striated, which would be very unlikely in a pure melt-out processes (ice does not striate rock). Based on these features, it was determined that the Hartlen Till could still be considered a lodgement till, as pebble fabric is only one method of defining till deposition. The higher than expected eigenvalues (according to Dowdeswell and Sharp, 1986) may be due to the difference in the clast abundances and shear strength of the Hartlen Till compared to the tills used by Dowdeswell and Sharp.

5.2 Adjusting measured concentration for decay

The ^{10}Be concentrations that were measured (C_m) are the sum of the ^{10}Be concentration inherited from pre-glacial exposure (C_{inh}) and any post depositional ^{10}Be produced in the quartz since deposition (C_{pd}). However, the goal of the isotope tracer geochemistry is to determine the concentration of ^{10}Be initially in the quartz at the time of till deposition (C_i). Because C_{inh} is C_i minus the ^{10}Be lost due to decay since depositional time (t), (C^t_{decay}), it is possible to solve for C_i as follows:

$$C_m = C_{inh} + C_{pd} \tag{5.1}$$

$$C_{inh} = C_i * e^{-\lambda t} \tag{5.2}$$

The post-depositional concentration depends on the in situ production rate of ^{10}Be in the grains of sand sampled, which varies according to cliff erosion rate and average slope of the cliff, and the production by muons to the depths of the samples. To calculate the post-depositional production, we computed an in situ ^{10}Be production rate based on (i) the Lal (1991) and Stone (2000) scaling factors for latitude (44.64°N), elevation (average about 0 m above sea level; although this varied due to isostasy and sea level change, the production rate is not significantly affected), and topographic shielding of the sample site; and (ii) the recent erosion rate of the drumlin sea cliff. Because the samples are near sea level and at >8 m depth, and because the section was covered by glacier ice for a considerable fraction of the post-Hartlen Till depositional time (t), the muons have produced very few atoms in the Hartlen Till. The till cliff retreat rate was estimated by (a) observation of the distance of land loss to coastal erosion for the last three decades according to the landowner Carol O'Neal, and (b) measurements of drumlin coastal erosion rates from Piper et al. (1986).

The landowner estimates that 6 ft. of sediment has eroded over 25 years, resulting in a short term erosion rate of 7 cm/a. For similar till sections, the century-scale erosion rate for Nova Scotian coasts is 25 cm/a (Piper et al., 1986). Because the landowner's estimate is probably a closer indication of the erosion rate of this particular location, we assume that the erosion rate is 7 cm/a. The conservative value will also reduce the consequence of having slower rates of exhumation in the late Holocene. Note, however, that even at only 7 cm/a erosion rate, the net in situ production of ^{10}Be is so low that the quartz sampled would have only been influenced by variations in the rate of erosion over the last century or less anyway. The C_{pd} can be calculated from equation 5.3,

$$C_{pd} = \frac{P}{(\rho\varepsilon\Lambda^{-1}+\lambda)}(1 - e^{-\rho\varepsilon\Lambda^{-1}+\lambda)t}) \quad (5.3)$$

where P is production rate, t is maximum exposure time since deposition, ρ is the density of the till (2 g cm^{-3}), ε is the erosion rate, Λ is the attenuation length of fast neutrons (150 g cm^{-2}), and λ is the decay constant of ^{10}Be. The ^{10}Be λ has been recently revised. Two separate studies conducted in 2010 used multicollector ICP-MS and liquid scintillation counting to determine the new half-life of ^{10}Be and yielded very similar results. Chmeleff et al. (2010) determined the half-life to be 1.386 ± 0.016 Ma; while Korschinek et al. (2010) found the 1.388 ± 0.018 Ma. Therefore, 1.387 ± 0.017 Ma is the revised half-life of ^{10}Be, corresponding to a decay constant of 4.997 x 10^{-7} a^{-1}. The calculated C_{pd} enabled us to determine that ~42 atoms/g of quartz were produced in the post-depositional environment. This value is three orders of magnitude lower than C_m (Table 4.2), indicating a high inheritance concentration.

The ^{10}Be in the Hartlen Till has been decaying for approximately 63 ka, the average of 75 and 50 ka (the duration of the Caledonia Phase of glaciation during which the Hartlen till was deposited (Stea and Pe-Piper, 1999). From equation 5.2 and the decay duration specified,

$$C_{inh} = 0.97*C_i \quad (5.4)$$

and from equation 5.1 it follows that:

$$C_{inh} = C_m\text{-}42 \quad (5.5)$$

The correction C_{pd} ^{10}Be should be approximately similar for both tills. Thus, for each of the samples,

$$C_i = \frac{(C_m - 42)}{0.97} \quad (5.6)$$

Table 4.2 provides the calculated initial concentrations in the Hartlen Till at the time of deposition.

5.3 Comparison of the C_i in Lawrencetown Till and Hartlen Till

The older Hartlen Till has initial concentrations between 6.63 x 10^4 and 8.58 x 10^4 atoms/g, while the two samples taken from the overlying Lawrencetown Till both had concentrations of about 1.60 x 10^4 atoms/g (Fig. 5.1; Fig. 5.2). There are three explanations for this significant difference in concentrations. It was hypothesized before sampling that because the Hartlen Till was deposited first, it would likely show the highest concentrations due to the prolonged exposure of the source sediments to cosmic rays during the OIS 5 interglacial. Furthermore, the Lawrencetown Till may comprise sediment derived from a relatively more deeply exhumed source due to the additional glacial erosion

associated with OIS 2 and 3. If so, the Lawrencetown Till would have a lower initial concentration than the Hartlen Till because the Hartlen Till source sediment was exposed near the surface for a longer time.

A second explanation for the difference in the concentrations in these two tills is that their sediment derived from different sources and that the production rate of ^{10}Be at these locations was significantly different (by about 5x). Evidence to support this explanation is from differences in clast types, matrix colour and level of compaction observed in the field as noted by many authors (e.g. Nielsen, 1976; Stea, 2004). Production rates of ^{10}Be at 300 m are 1.3 X greater than production rates at sea level. Because the elevations and latitude of the sources of the two tills are not significantly different, this explanation is not possible.

A third explanation regards the possibility that the C_i in the two tills were similar, but that the Hartlen Till is older than interpreted. If the Hartlen Till was deposited during OIS 6, it would have experienced a very long exposure to cosmic rays during OIS 5 interglaciation. Were this the case, an approximately exponential decrease in concentration with depth should have been observed (Fig. 1.1) due to the attenuation of cosmic ray flux through the exposed till during the long OIS 5. This is not the case. However, it is not possible to preclude the possibility that most of the hypothetically exposed Hartlen Till was eroded during the Scotia phase—some erosion is expected, and grain size in the Lawrencetown Till does coarsen upward from the finer Hartlen Till). By eroding enough sediment, the shape of the vertical profile would shift from the neutron dominated significant exponential decrease, to a weaker decrease (approaching the uniform distribution observed) at great depths. More than 6 m of till would have had to have been eroded to lower the in situ produced ^{10}Be concentration pattern to an apparently uniform

distribution. However, at such depths, the C_{pd} produced over 60,000 year interglacial would be on the order of 100 atoms/g. This is two orders of magnitude too small to explain the difference in the C_m in the two tills.

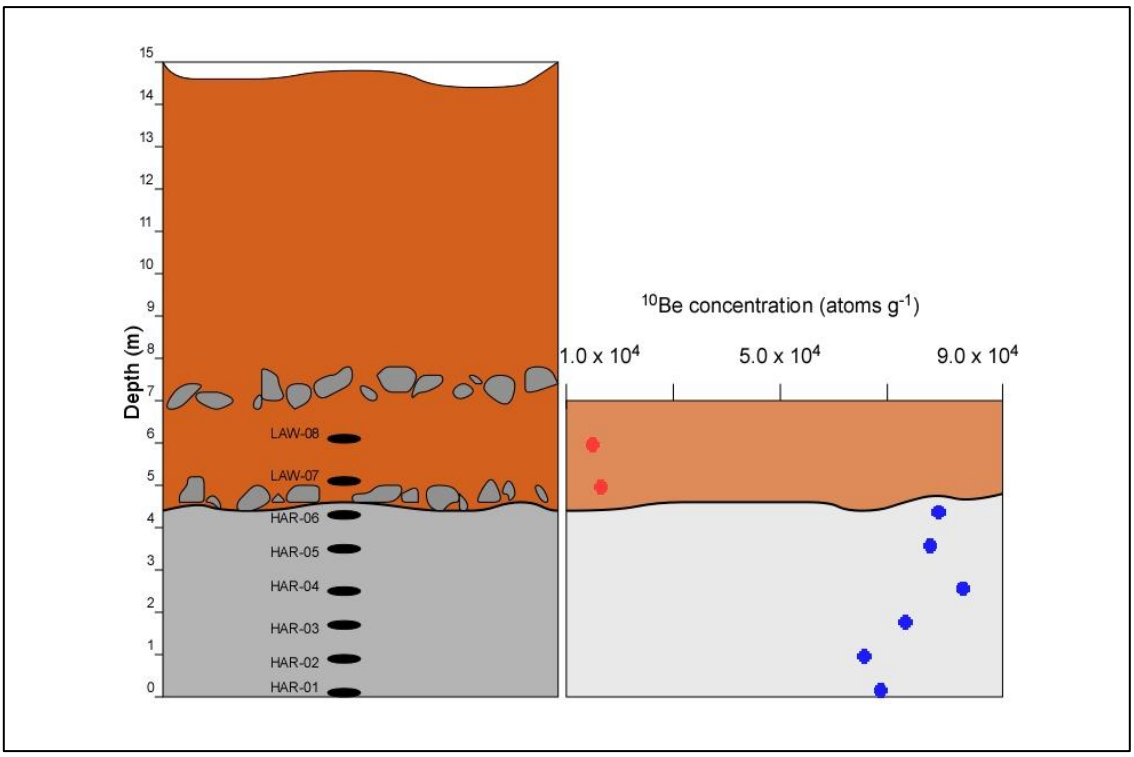

Figure 5.1: Schematic drawing of the study area with sample sites shown. Sample sites are matched to the ^{10}Be concentration calculated from the PRIME lab AMS data (Fig. 5.2). This demonstrates the marked difference in concentrations between the two tills.

Thus, it can be deduced that the sharp decrease in ^{10}Be concentration above the contact between these two tills is mainly a function of ice cover history. The Lawrencetown Till must have derived from a more shielded (i.e. from a more deeply eroded) source than the Hartlen Till which derived from regolith that was exposed at the surface for the duration of the OIS 5 interglacial.

5.4 Hartlen Till Concentration vs. Depth Profile

The C_i vs. depth profile in the Hartlen Till displays a relatively uniform vertical trend, but it can be observed that the highest concentrations lie in the samples taken from the top of the Hartlen Till (Fig. 5.2). Unfortunately, due to the small number of samples as well as the strong overlap of 2 sigma precision, this trend is difficult to define. It can be inferred that this till section was deposited after an extended period of transportation which caused the homogenization and mixing of the till material. The sample HAR-04 can be used to verify that this till has been well mixed. This sample in the middle of the Hartlen Till section contained the highest concentration, which was unexpected due to its position in the till. One would expect the stratigraphically higher samples in the Hartlen Till to have the highest concentration if post depositional exposure to cosmic rays was significant. It can be inferred that some of the material taken from HAR-04 was located at surface at its source, but due to the glaciation, this material was mixed until it was deposited in the middle of the section.

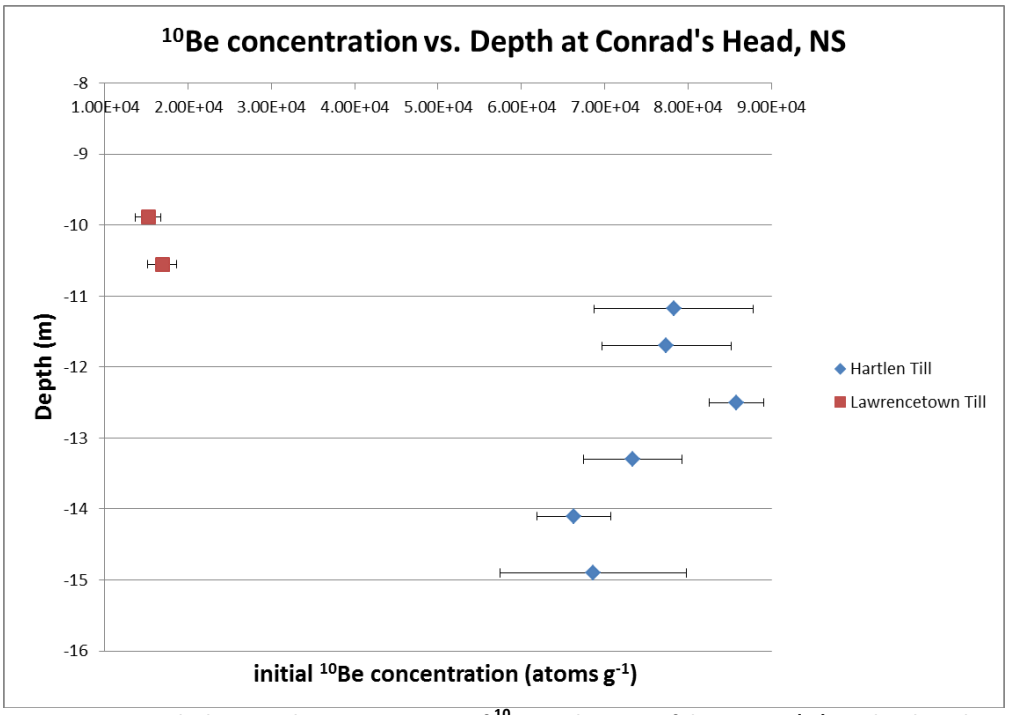

Figure 5.2: A graph showing the concentration of ^{10}Be at the time of deposition (Ci) vs. depth with 2σ error.

Another possible explanation for the HAR-04 elevated concentration is that the till taken from samples HAR-01 to HAR-04 were deposited before samples HAR-05 and HAR-06. If we isolate these four points, a general trend of increasing concentration can be observed. This would suggest that the Hartlen Till was deposited in two stages. This would indicate that samples HAR-01 through HAR-04 were deposited first and then more material was taken from a slightly different source during the same glaciation. One would expect that this more deeply eroded material would have a lower concentration than the first till. If there was a short interglacial between the deposition of the two hypothetical layers of Hartlen Till a short period of exposure would allow the higher samples to produce more ^{10}Be. This hypothesis is less likely because the Hartlen Till otherwise seems to be very homogenized, and there were no indications of different erratic material or erosional slope of the coastal section (different material in till erodes at different rates, i.e. the Hartlen Till has a much steeper slope than the overlying Lawrencetown Till). While it is possible that there were readvances and that this section was near the ice margin more than twice during the OIS 4 glaciation, there is no other evidence to support this explanation. Thus, the small variation in C_i with depth in the Hartlen Till may best be explained as scatter due to a combination of measurement precision and incomplete mixing of the till during transportation from the source area.

5.5 Deformation of the Deformable Bed

The AMS results have allowed us to make some important observations regarding the presence of the deformable bed within the Hartlen Till. From our six samples within the

Hartlen Till, a relatively uniform vertical trend can be observed in ^{10}Be concentrations when 2σ error is taken into account (Fig. 5.2). This trend in the data best resembles Scenario (i) from Hypothesis (2) (Fig. 1.1). This trend signifies that the Hartlen Till was well-mixed (although not completely, see section 5.3), which implies a substantial transportation distance. This trend also implies that the deformable bed must be at least the thickness of the Hartlen Till that is exposed at Conrad's Head (~6.2 m). A thickness of this extent corresponds well to 5-6 m of the soft sediments detected under Ice Stream B by Alley et al. (1986). It can then be assumed that a deformable bed has the capacity to reach thicknesses of at least 5 m given the required subglacial conditions.

It should also be noted that at least several meters of the base of the Hartlen Till cannot be observed at Conrad's Head. Therefore, it is possible that in a completely exposed section of the Hartlen Till, a trend resembling Scenario (ii) (Fig. 1.1) would be visible in a ^{10}Be concentration vs. depth profile. Part of the motivation behind choosing the Hartlen Till as a test site for this method was due to its lateral continuity across the province of Nova Scotia. Given that the method of using ^{10}Be as a tracer for subglacial deformation appears to be effective, it would be useful to employ this method at a site where the entire Hartlen Till was exposed. This would help determine if the entire section displayed the same vertical trend as the Conrad's Head section, or whether higher concentrations could be observed at the base.

5.6 Implications and Recommendations for Future Work

As it can be confirmed that there was not an extended interglacial period between the deposition of the Hartlen and Lawrencetown tills, hypotheses can be made in regards to the

stone line. One of the original hypotheses was that during this extended interglacial period, sediments were deposited and then eroded during the deposition of the Lawrencetown Till, leaving only the large boulder clasts behind. Since it is now known that this extensive interglacial did not take place, we can infer that the stone line was formed according the the Hart (1998) model (Fig. 2.2), as a subglacial erosional lag of the larger clasts during the deposition of the Lawrencetown Till.

Also, as previously mentioned, it may be useful to utilize ^{10}Be as a tracer in another Hartlen Till section in Nova Scotia. Doing so would provide insight on whether the vertical trend visible in this data was consistent throughout the entire Hartlen Till, and if higher concentrations could be observed at the base.

It was demonstrated that there was a high ^{10}Be C_{inh} in the Hartlen Till. This concentration overwhelmed the C_{pd}, which has implications on other applications of TCN in Nova Scotia. For instance, ^{10}Be is commonly used to determine outcrop and catchment erosion rates, but this application may not be useful in Nova Scotia. Due to the high rates of erosion sea cliff erosion and high C_{inh}, cosmogenic ^{10}Be cannot be produced in significant post-depositional quantities in a coastal region of Nova Scotia to be isolated from the C_{inh}. Other applications will depend on whether or not other tills have lower C_{inh} than the Hartlen or Lawrencetown Till, or whether erosion rates in catchments or other coastal regions are sufficiently slow to permit the buildup of C_{pd}.

Through this study, it appears that using cosmogenic isotopes in till is an effective way to gain a better understanding of glacial history. This method can now be applied to other till sections globally that have constraints on glacial flow direction, age, and depositional processes. To confirm the validity of the results found at Conrad's Head, it may be wise to

take more samples in another area within the drumlin at the same depths to prove that the AMS results are reproducible.

6.0 Conclusions

(1) Hypothesis H1 has been supported. Based on differences in composition and ^{10}Be it can be assumed that the Hartlen Till and Lawrencetown Till originated from regolith that experienced significantly different glacial and therefore exposure histories (i.e. that the Lawrencetown Till source was relatively more deeply eroded and less exposed prior to entrainment).

(2) The high concentration of ^{10}Be observed in the Hartlen Till indicates that the Sangamonian interglacial period (~125-75 ka) was a sufficient duration of time to produce measurable concentrations of ^{10}Be. In contrast, the period between the deposition of the Lawrencetown and Hartlen tills (~50-24 ka) did not have a sufficiently long period of ice-free time in which to produce significant concentrations of ^{10}Be in the Lawrencetown Till. This is consistent with inferred glacial dynamics over the OIS 3 and 2 stages.

(3) Of the five scenarios that were anticipated to be represented by the Hartlen Till ^{10}Be vs. depth profile, the measured trend best corresponds with scenario (i). From this we can infer that the deformable bed can reach thicknesses of at least 5-6 m before becoming unstable.

(4) Scenario (ii) cannot be ruled out, because the base of the Hartlen Till is not visible at the Conrad's Head study site.

(5) The method of using ^{10}Be as a tracer for subglacial processes was successful, supporting H2, and can be applied in other till sections where a deformable bed is likely to be present.

(6) ^{10}Be concentrations may not be useful to determine erosion rates on coastal Nova Scotia, due to the relatively low quantities of post-depositional production. The low post-

depositional production is a result of the high erosion rates prohibiting any accumulation of post-depositional ^{10}Be.

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Glossary

AMS	Accelerator Mass Spectrometry
Ancient till	An unlithified till that is no longer actively being deposited; in other words, a paleo-till, but not a tillite
Caledonian Phase	The first stage in the Wisconsinan glacial period. Took place from ~75-50 ka. It was during this stage that the Hartlen Till was deposited at Conrad's Head and across Nova Scotia.
Deformable Bed	A subglacial feature observed under active glaciers in which unconsolidated sediments move together as a unit as a result of shear stress induced by the overlying glacier, accounting for a large portion of glacial movement.
Diamicton	A non-genetic term describing a massive, poorly sorted, matrix supported sediment. Although at a coarse scale homogeneity is common, at a cm-scale or less the diamicton may contain sedimentary structures formed during deposition or post-depositional deformation (e.g. sand wisps or shear bands). Most tills in Nova Scotia are diamictons, although there is a wide range in the abundance and size of clasts and the composition of the matrix.
Inherited concentration	The concentration of a TCN from a previous exposure. To determine the original concentration in the till at the time of deposition, any radioactive decay of the *initial concentration* must be added
Isotope	An atom with a nucleus of one or more protons and a similar but not necessarily equivalent number of neutrons, with a charge-balancing number of electrons
LIS	Laurentide Ice Sheet
Nuclide	A nucleus of an atom consisting of one or more protons and zero or more neutrons, but with no electrons
Initial concentration	The concentration of a TCN at the time of deposition in a till.
Scotian Phase	The second stage in the Wisconsinan glacial period. Took place from ~24-20 ka. It was during this stage that the Lawrencetown Till was deposited at Conrad's Head and across Nova Scotia
Stone line	A non-genetic term for a plane of boulders or cobbles within a sedimentary unit; the stone line thickness is usually one stone, and in a till the space between the stones will be matrix
TCN	Terrestrial Cosmogenic *Nuclide*
Till	Sediment deposited directly by glacier ice that has not undergone subsequent disaggregation and resedimentation.
Till fabric	Description of the strength and orientation of the long axis of a number of stones of a specified geometry in a till. Pebble

	fabric or diamicton macrofabric analysis measured using clasts in till.
Decay constant	The constant ratio for the number of atoms of a radionuclide that decay in a given period of time compared with the total number of atoms of the same kind present initially.
Half life	Time required for an isotope undergoing decay to reach one half of its initial quantity.
Attenuation length	The distance into a material in which a secondary cosmic ray can travel without significant production of nuclides.
Production rate	The rate at which a cosmogenic isotope is produced in a material, influenced by changes in the magnetic field over time, as well as a cosmic ray's angle of incidence to the magnetic field.
Post-depositional TCN production	Nuclides that are produced within a geologic feature after it has been deposited. This value needs to be corrected for in many TCN applications because most processes are traced by the concentration of cosmogenic nuclides before the sediments were deposited.
^{10}Be	A cosmogenic nuclide that is formed through spallation reactions. Has a half-life of 1.387± 0.017 Ma

Appendix A: Hartlen Till Pebble Fabric Data

TF1 (Right side)

#	Azimuth (°)	Plunge (°)	Lithology	A (cm)	B (cm)	C (cm)	Proximity to Other Clasts
1	2	28	greywacke	8	4	2	
2	325	24	greywacke	6	3	2	
3	350	31	greywacke	14	6	6	
4	6	23	granitoid	8	4	3	*
5	308	13	greywacke	8	5	3	
6	348	25	greywacke	4	2	1	
7	340	14	greywacke	5	3	2	
8	351	34	greywacke	5	3	2	*
9	324	33	greywacke	5	3	1	
10	12	2	greywacke	8	3	3	
11	330	22	greywacke	5	3	2	
12	352	38	greywacke	4	2	2	
13	359	21	greywacke	5	3	1	
14	340	32	greywacke	10	6	3	
15	310	41	greywacke	7	3	2	
16	330	23	greywacke	6	4	2	
17	304	18	slate	8	3	1	
18	324	2	greywacke	8	4	3	
19	330	9	greywacke	4	2	1	
20	343	42	granitoid	4	2	1	
21	340	47	greywacke	6	3	2	
22	318	17	greywacke	5	4	2	
23	12	18	greywacke	4	2	1	
24	342	44	granitoid	6	4	3	
25	346	41	greywacke	16	8	5	*

TF2 (Left side)

#	Azimuth (°)	Plunge (°)	Lithology	A (cm)	B (cm)	C (cm)	Proximity to Other Clasts
1	355	37	greywacke	4	2	2	
2	350	13	greywacke	6	3	2	
3	342	18	greywacke	7	3	2	
4	4	15	greywacke	5	3	2	
5	24	10	greywacke	5	3	2	
6	336	13	greywacke	6	3	1	
7	327	10	greywacke	13	5	4	*
8	332	18	greywacke	9	5	3	
9	358	27	greywacke	11	6	4	
10	22	23	greywacke	6	2	1	*
11	328	11	greywacke	10	5	4	
12	12	39	greywacke	5	3	1	
13	325	23	greywacke	4	2	1	
14	52	11	granitoid	6	3	2	
15	336	19	greywacke	8	5	3	*
16	312	9	greywacke	5	3	2	
17	12	32	greywacke	6	3	2	
18	346	28	greywacke	5	3	2	
19	3	42	greywacke	7	4	2	
20	13	14	greywacke	7	3	2	
21	343	21	greywacke	6	4	2	
22	344	34	greywacke	7	4	2	
23	348	28	greywacke	12	6	4	
24	32	35	greywacke	5	3	2	
25	342	25	greywacke	12	5	3	

* Indicates that this clast was in close proximity to another pebble

Appendix B: Chemical Worksheets

WS4_QtzDissolution

This worksheet outlines the steps for dissolving quartz and adding Be carrier.

JG/GY

Chemist: GY

form:mm/dd/yy

Date: 11/07/11

	1	2	3	4	5	6	7	8	9
CNEF ID	2739	2740	2741	2742	2743	2744	2745	2746	2640
Sample ID	NS-11-HAR-01	NS-11-HAR-02	NS-11-HAR-03	NS-11-HAR-04	NS-11-HAR-05	NS-11-HAR-06	NS-11-HAR-07	NS-11-HAR-08	blank
300 ml vessel ID	B1	B13	B17	B20	B23	B25	B26	B32	B8
Beryl Carrier ID	Be carrier 3, Bottle 2 dec 10, 2011								
Al Carrier ID	No Al data needed,								
Mass 300 ml vessel	Use stainless steel holder to weight samples. (plastic beaker is static to make balance sensitive move)								
rtz <250um protion	75.0406	75.019	75.0054	75.0113	75.0118	75.0071	75.0001	75.0022	
total quartz mass	95.2567	95.0050	95.0103	95.0148	95.0362	95.0190	95.0018	95.0910	0
Mass Be carrier	0.1898	0.1959	0.1801	0.1869	0.1844	0.2108	0.1821	0.1877	0.1910

SAVE AS: C:/Chemistry/CHEM_WK YYMMDD .xls then PRINT

- $_1$ Add 20 ml conc. HF and 2 ml $HClO_4$ per 5 g of quartz
- $_2$ Add 5 ml Aqua Regia
- $_3$ Heat at 100-125^o C until quartz dissolves, add HF if needed
- $_4$ Raise to 200^o C and evaporate to dryness
- $_5$ Add 5 ml $HClO_4$ and evaporate to dryness
- $_6$ Add 8 to 10 ml conc. HNO_3, swirl, and evaporate to dryness
- $_7$ Dissolved dried sample in 20 ml of 2% HCl(for Al Aliquot, use 2%HNO3)

Comments

Guang:

Logan's till samples include 2 parts, <250um and 250-500um, use ~75g for fine parts and 20g others to make 95g each

These samples have no Al test done.

WS6_Anion Column Chemistry

This worksheet outlines the steps for the Anion Column Chemistry

Chemist: GY **Date:** form: MM/DD/YY

Print this page

- 1 Evaporate 80 ml to dryness at 100-120°C (will take at least 3 hrs)
- 2 Dissolve in 10 ml 9N HCl (let stand for several hours)
- 3 Transfer to 15 ml centrifuge tubes, rinse digestion vessels with 9N HCl to bring volume in tube to 10 ml
- 4 Centrifuge at 1500 rpm or higher for minimum of 10 minutes
- 5 Allow any 9 N HCl in columns to drain out; discard

Column ID	A	B	C	D	E	F	G	H	I	AnionColumnID
Vessel	B1	B13	B17	B20	B23	B25	B26	B32	B8	
CNEF ID	2739	2740	2741	2742	2743	2744	2745	2746	2640	105
Sample ID	NS-11-HAR-01	NS-11-HAR-02	NS-11-HAR-03	NS-11-HAR-04	NS-11-HAR-05	NS-11-HAR-06	NS-11-HAR-07	NS-11-HAR-08	blank	WY-96-001

- 6 With stopcock closed, pipet sample (avoid residue)onto 19ml resin columns.
- 7 Collect sample in same (wiped)120 ml teflon vessel
- 8 Elute with 30 ml 9 N HCl, and collect that, close stopcock
- 9 5 ml 4.5 N HCl, collect Anion Supernate in labeled 100 ml bottle
- 10 100 ml 1 N HCl, collect Anion Supernate
- 11 50 ml deionized water. Discard.
- 12 **CONDITION ANION COLUMN**

(bottle A1) 50 ml 1N HCl, discard
(bottle A2) 50 ml 4.5 N HCl, discard
(bottle A3) 100 ml 9 N HCl, discard, but retain acid approx. 2 mm above resin

Comments

WS6_Anion Column Chemistry

This worksheet outlines the steps for the Anion Column Chemistry (6ml size small column)

Start Nov 14, 2011, We are going to use 6ml size anion columns for all samples. If high Fe and Ti, we need run 2times

GY

Chemist: [ ]

form: MM/DD/YY

Date: [ ]

If we don't need any Al-26 data, we could skip Step WS5.

- 1 Evaporate 20 ml to dryness at 100-120^{o}C (will take at least 3 hrs)
- 2 Dissolve in 10 ml 9N HCl (let stand for several hours)
- 3 Transfer to 15 ml centrifuge tubes, rinse digestion vessels with 9N HCl to bring volume in tube to 10 ml
- 4 Centrifuge at 1500 rpm or higher for minimum of 10 minutes
- 5 Allow any 9 N HCl in columns to drain out; discard

Column ID	A	B	C	D	E	F	G	H	I	AnionColumnID
Vessel	B1	B13	B17	B20	B23	B25	B26	B32	B8	
CNEF ID	2739	2740	2741	2742	2743	2744	2745	2746	2640	105
Sample ID	NS-11-HAR-01	NS-11-HAR-02	NS-11-HAR-03	NS-11-HAR-04	NS-11-HAR-05	NS-11-HAR-06	NS-11-HAR-07	NS-11-HAR-08	blank	WY-96-001

- 6 With stopcock closed, pipet sample (avoid residue)onto 6ml size columns.
- 7 Collect sample in same 300 ml teflon vessel.
- 8 Elute with 30 ml 9 N HCl, and collect that, close stopcock
- 9 6 ml 4.5 N HCl, collect Anion Supernate in labeled 100 ml bottle
- 10 30 ml 1 N HCl, collect Anion Supernate
- 11 50 ml deionized water. Discard.
- 12 **CONDITION ANION COLUMN**

(bottle A1) 10 ml 1N HCl, discard
(bottle A2) 10 ml 4.5 N HCl, discard
(bottle A3) 10 ml 9 N HCl, discard, but retain acid approx. 2 mm above resin

Comments

WS7_Controlled Precipitate

This worksheet outlines the steps for the controlled precipitation chemistry

GY
Chemist: [ ]

form: MM/DD/YY
Date: [ ]

Print this page

- 1 Evaporate "anion" elute to dryness at 125°C
- 2 Dissolve in 10 ml of a 1:1 solution of 0.5N HCl and 2% NH_4Cl
- 3 Transfer to 15 ml centrifuge, centrifuge for 10 minutes
- 4 Decant into clean test tube, heat in water bath at 60°C
- 5 Add drops of 1:1 NH_4OH:H_2O to pH=9.2 (5 drops first then single)
- 6 Centrifuge for 15 minutes
- 7 Check pH of liquid, if less than pH=7, redo step • 5
- 8 Decant, save with Anion Supernate
- 9 Wash with deionized water, vortex, centrifuge, decant

CNEF ID	2739	2740	2741	2742	2743	2744	2745	2746	2640	105
Vessel	B1	B13	B17	B20	B23	B25	B26	B32	B8	
Sample ID	NS-11-HAR-01	NS-11-HAR-02	NS-11-HAR-03	NS-11-HAR-04	NS-11-HAR-05	NS-11-HAR-06	NS-11-HAR-07	NS-11-HAR-08	blank	
Approx. vol. Ptte										

Comments

WS8A_Pre-Cation Column Chemistry

For Samples with high Al, need two run to get better Be

Chemist: GY/JG **Date:** mm/dd/yy

Print this page

- 1 Dissolve in 5 ml conc. HCl and evaporate to dryness at 125^{o}C
- 2 Redissolve in 2.5 ml 1N HCl and 2.5 ml 0.5 N HCl
- 3 Transfer to centrifuge tube, rinse with 1 ml 0.5N, and centrifuge

Column ID	1	2	3	4	5	6	7	8	9
Vessel	B1	B13	B17	B20	B23	B25	B26	B32	B8
CNEF ID	2739	2740	2741	2742	2743	2744	2745	2746	2640
Sample ID	NS-11-HAR-01	NS-11-HAR-02	NS-11-HAR-03	NS-11-HAR-04	NS-11-HAR-05	NS-11-HAR-06	NS-11-HAR-07	NS-11-HAR-08	blank

- 4 **Pipette all of the sample into designated conditioned cation column, 17ml**
- 5 Discard the eluant.
- 6 Add 285 ml 0.5 N HCL (Bottle 6)
- 7 Drain the column, discard the 250ml of eluant
- 8 Add 250ml 1.0 HCl, (Bottle 7), Collect eluent as Be-sample
- 9 Add 100 ml 4.5 N HCl (bottle 10) , save the eluant as Al sample.

10 **CONDITION CATION COLUMN**

(bottle C1) 100 ml 9N HCl
(bottle C2) 50 ml 4.5 N HCl
(bottle C3) 50 ml 1 N HCl
(bottle C4) 50 ml water
(bottle C5) 100 ml 0.5 N HCl

* 17 ml Column

WS8_Cation Column Chemistry

This worksheet outlines the steps for the Cation Column Chemistry

Chemist: GY/JG **Date:** mm/dd/yy

Print this page

- 1 Dissolve in 5 ml conc. HCl and evaporate to dryness at 125°C
- 2 Redissolve in 2.5 ml 1N HCl and 2.5 ml 0.5 N HCl
- 3 Transfer to centrifuge tube, rinse with 1 ml 0.5N, and centrifuge

Column ID	1	2	3	4	5	6	7	8	9	examples
Vessel	B1	B13	B17	B20	B23	B25	B26	B32	B8	
CNEF ID	2739	2740	2741	2742	2743	2744	2745	2746	2640	105
Sample ID	NS-11-HAR-01	NS-11-HAR-02	NS-11-HAR-03	NS-11-HAR-04	NS-11-HAR-05	NS-11-HAR-06	NS-11-HAR-07	NS-11-HAR-08	blank	WY-96-001

- 4 **Pipette all of the sample into designated conditioned cation column, 17ml**
- 5 Discard the eluant. Add 285 ml 0.5 N HCL (Bottle C6)
- 6 **Drain the column, discard the first 300ml of eluant**
- 7 Add 60ml of 0.5N HCl, (Bottle 7), Collect eluant as Cation Supernate
- 8 Add 65ml of 0.5N HCl, (Bottle 8), Save it as Be-Sample
- 9 Add 120 ml 1N HCl (bottle9)
- 10 Save this as Be-sample as well.
- 11 Add 80 ml 4.5 N HCl (bottle 10) , save the eluant as Al sample.
- 12
- 13 **CONDITION CATION COLUMN**

(bottle C1) 100 ml 9N HCl
(bottle C2) 50 ml 4.5 N HCl
(bottle C3) 50 ml 1 N HCl
(bottle C4) 50 ml water
(bottle C5) 100 ml 0.5 N HCl

* 17 ml Column

WS9_Be Sample Chemistry

This worksheet outlines the steps to prepare the BeO sample

Chemist: GY **Date:** form: mm/dd/yy

Print this page

- 1 Evaporate Be Sample from column in wiped digestion vessels at 125°C
- 2 Add 2-5 ml 20% perchloric and evaporate at 200oC
- 3 Again, add 2-5 ml 20% perchloric and evaporate at 200°C
- 4 Dissolve sample in 10 ml of 0.5 N HCl (optima grade)
- 5 Transfer to 15 ml centrifuge tube
- 6 Centrifuge and decant into clean centrifuge tube
- 7 Heat centrifuge tubes in water bath at 60°C
- 8 Precipitate $Be(OH)_2$ using Matheson ultimate grade ammonia gas

  Gently bubble NH_3 with clean pipet tip on hose

  for ca.15 bubbles, or ca. 8-12 sec until ptte forms

  Optimum pH=9.2; 1N HCl may be added
- 9 Centrifuge 15 min., decant (save and redo • 8 if pH of liquid is < 8)
- 10 Wash with water, vortex, centrifuge for 10 min, and decant
- 11 Record mass quartz vials, label, and place them in furnace holder

CNEF ID	2739	2740	2741	2742	2743	2744	2745	2746	2640
Vessel	B1	B13	B17	B20	B23	B25	B26	B32	B8
Sample ID	NS-11-HAR-01	NS-11-HAR-02	NS-11-HAR-03	NS-11-HAR-04	NS-11-HAR-05	NS-11-HAR-06	NS-11-HAR-07	NS-11-HAR-08	blank
Mass Qtz Vial									
Mass Vial+Spl									
Mass Spl	0	0	0	0	0	0	0	0	0

- 12 Add 1 small drop of water with micropipet, slurry precipitate
- 13 Transfer sample into quartz vial, cover with quartz lid
- 14 Turn on Bunsen Burner, dry the gel carefully.
- 15 Burn the Be(OH)2 gel on bunsen burner at least 2 mins, at blue flame.
- 18 Convert to BeO
- 19 Determine mass of vial + sample

Appendix C: AMS data for ^{10}Be analysis

Lab Sampleid	Field ID	SampleName	10Be/Be	Error(E-15)	Error%	AvgCuurent(nA)
201103832	blank	2640	18	6	35.5	449
201103841	HAR-01	2739	510	40	7.2	508
201103842	HAR-02	2740	477	13	2.7	2697
201103843	HAR-03	2741	572	20	3.5	1747
201103844	HAR-04	2742	641	21	3.3	2105
201103845	HAR-05	2743	589	27	4.5	1963
201103846	HAR-06	2744	520	30	5.9	1874
201103847	LAW-07	2745	145	7	4.7	2294
201103848	LAW-08	2746	129	6	4.7	2599

standard: Standard used is: Nishiizumi Be-01-5-3:6320(E-15).

Appendix D: Calculations to condense AMS data

					lat	elev	Lal scaling	
					44.64	15	0.98	
Objective1: correct for decay of concentrations								
Objective2: determine the in situ produced concentration								
	variable list							
		^{10}Be half life	t05Be	1.387	Ma			
		^{10}Be decay constant	lambdaBe	4.99746E-07	per year			
		prate in situ High Lat Sea Level	prodBe	4.76	atoms/g per year			
		at site, in situ prod rate	prodBesite	4.6648	atoms/g per year		for a flat 2pi surface	
		shielded correction	shieldfactor	0.85	unitless		15% shielding	
		time since Hartlen deposition	tH	62500	yr			
		time since Lawrencetown dep	tL	22000	yr			
		measured Cm (corr for blank/bkg	Cm	66500	atoms/g		blank corrected concentrat	
		measured inh C	Cinh	66458	atoms/g		Cm=Cinh-Cpd	
		initial concentration in Hartlen	Ci	68566	atoms/g		Cinh=Ci*e(-lambda t)	
		post dep C	Cpd	42	atoms/g			
		erosion rate	erosrate	7	cm/a			
		bulk density	density	2	g cm^-3			
		attenuation length	attenL	150	g cm^-2			
Objective 1								
		Cinh = Cm-Cpd		6.65E+04				
		Ci = Cinh/exp(-lambdabe*tH)		6.86E+04				
Objective 2		Cpd						
		corrected In situ prodrate		3.96508	atoms/g per year, corr for shielding			

$$N = \frac{P}{(\rho\varepsilon\Lambda^{-1} + \lambda)}(1 - e^{(\rho\varepsilon\Lambda^{-1}+\lambda)t})$$

		assume that the coast was deglaciated at 15000						
		42	atoms/g of quartz produced post depositionally in the samples collected					

Appendix E: AMS Spreadsheet

CNEF ID	Be AMS ID	Al AMS ID	Field ID	Latitude	Longitude	Elevation	Alt tag	Thickness	Density	Shielding	Erosion Rate	10Be in qtz conc	10Be in qtz error	AMS std tag
(txt)	(txt)	(txt)	(txt)	(d.d)	(d.d)	(m)	(std)	(cm)	(g/cm3)	(unitless)	(cm/a)	(atom/g)	(atom/g)	(Cronus)
JG1234	BE12345	AL12346	XX-09-XX	45.678	-70.123	1234	std	2	2.6	0.987	0.00001		TOTAL ERROR 1σ	07KNSTD
JG-2640	201103832		Blank for 20111107											
template	template		template	38.58	-109.522	1442	std	3	2.3	0.980	0	2.04E+06	51625	KNSTD
JG-2739	201103841		HAR-01	44.64	-63.36	2		13	2		7	6.65E+04	5.43E+03	07KNSTD
JG-2740	201103842		HAR-02	44.64	-63.36	2.93		13	2		7	6.43E+04	2.17E+03	07KNSTD
JG-2741	201103843		HAR-03	44.64	-63.36	3.86		12	2		7	7.12E+04	2.87E+03	07KNSTD
JG-2742	201103844		HAR-04	44.64	-63.36	5.78		14	2		7	8.32E+04	3.19E+03	07KNSTD
JG-2743	201103845		HAR-05	44.64	-63.36	5.72		17	2		7	7.51E+04	3.76E+03	07KNSTD
JG-2744	201103846		HAR-06	44.64	-63.36	6.41		14	2		7	7.59E+04	4.63E+03	07KNSTD
JG-2745	201103847		LAW-07	44.64	-63.36	7.18		18	2		7	1.64E+04	8.55E+02	07KNSTD
JG-2746	201103848		LAW-08	44.64	-63.36	8.02		21	2		7	1.48E+04	7.49E+02	07KNSTD

re-stdardized concent (atom/g)	(atom/g)	Ratio atoms/atoms	Sample type (txt) boulder	CNEF ID (txt) JG1234	Qtz Mass (g) 40	Carrier Mass (g) 0.2	Carrier ID (txt) Becarrier	Carrier Conc (µg/mL) 1000	Carrier Density (g/mL) 1.013	9Be added (atoms 9Be)	Be Blank ID (txt) 1234	10Be/9Be blank boroncorr (10Be/9Be) 4.00E-15	10Be/9Be blank error (10Be/9Be) 4.00E-16	10Be in Process blank (atoms 10Be)
				JG-2640	0.0000	0.191	Be3-Carrier Bottle 2	1030	1.013	1.298E+19	JG-2640	1.84E-14	6.00E-15	2.388E+05
2.04E+06	5.16E+04			template	30.0000	0.2000	Be-Carrier Bottle 2	985	1.013	1.300E+19	JG-2640			
6.65E+04	5.43E+03		depth profile1	JG-2739	95.257	0.1898	Be3-Carrier Bottle 2	1030	1.013	1.290E+19				2.388E+05
6.43E+04	2.17E+03		depth profile1	JG-2740	95.005	0.1959	Be3-Carrier Bottle 2	1030	1.013	1.331E+19				2.388E+05
7.12E+04	2.87E+03		depth profile1	JG-2741	95.010	0.1801	Be3-Carrier Bottle 2	1030	1.013	1.224E+19				2.388E+05
8.32E+04	3.19E+03		depth profile1	JG-2742	95.015	0.1869	Be3-Carrier Bottle 2	1030	1.013	1.270E+19				2.388E+05
7.51E+04	3.76E+03		depth profile1	JG-2743	95.036	0.1844	Be3-Carrier Bottle 2	1030	1.013	1.253E+19				2.388E+05
7.59E+04	4.63E+03		depth profile1	JG-2744	95.019	0.2108	Be3-Carrier Bottle 2	1030	1.013	1.432E+19				2.388E+05
1.64E+04	8.55E+02		depth profile2	JG-2745	95.002	0.1821	Be3-Carrier Bottle 2	1030	1.013	1.237E+19				2.388E+05
1.48E+04	7.49E+02		depth profile2	JG-2746	95.091	0.1877	Be3-Carrier Bottle 2	1030	1.013	1.275E+19				2.388E+05

10Be/9Be AMS boroncorr (10Be/9Be) 5.00E-13	1σ Error (10Be/9Be) 9.00E-15	1s Error (fraction)	10Be atoms meas (atoms)	10Be atoms blnk subtr (atoms/g) in 1g quartz Cm	10Be atoms error (atoms 1σ) TOTAL (AMS+chem)	total error 1s fraaction	Post-depositional decay (number of atoms) Cpd	10Be atoms inherited (atoms/g) in 1g quartz Cinh=Cm-Cpd	10Be atoms initial (atoms/g) in 1 g quartz Ci
1.566E-13	3.973E-15	0.025	2.04E+06	2.04E+06					
				0.00E+00					
5.1E-13	4.00E-14	7.8%	6.58E+06	**6.65E+04**	**5.43E+03**	**0.082**	**42**	**6.65E+04**	**6.68E+04**
4.77E-13	1.30E-14	2.7%	6.35E+06	**6.43E+04**	**2.17E+03**	**0.034**	**42**	**6.43E+04**	**6.63E+04**
5.72E-13	2.00E-14	3.5%	7.00E+06	**7.12E+04**	**2.87E+03**	**0.040**	**42**	**7.11E+04**	**7.34E+04**
6.41E-13	2.10E-14	3.3%	8.14E+06	**8.32E+04**	**3.19E+03**	**0.038**	**42**	**8.31E+04**	**8.58E+04**
5.89E-13	2.70E-14	4.6%	7.38E+06	**7.51E+04**	**3.76E+03**	**0.050**	**42**	**7.51E+04**	**7.74E+04**
5.2E-13	3.00E-14	5.8%	7.45E+06	**7.59E+04**	**4.63E+03**	**0.061**	**42**	**7.58E+04**	**7.83E+04**
1.45E-13	7.00E-15	4.8%	1.79E+06	**1.64E+04**	**8.55E+02**	**0.052**	**42**	**1.63E+04**	**1.69E+04**
1.29E-13	6.00E-15	4.7%	1.65E+06	**1.48E+04**	**7.49E+02**	**0.051**	**42**	**1.47E+04**	**1.52E+04**