DEPOSITIONAL PROCESSES OPERATING ON THE PALEOPROTEROZOIC GOWGANDA ICE MARGIN

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ABSTRACT

Glacial sedimentary rocks of the Huronian Supergroup crop out along the north shore of Lake Huron and were likely deposited on what is thought to have been a divergent continental margin (Fralick and Miall, 1981; 1989). The rocks of the Gowganda Formation record one of three glacial events preserved in the Supergroup and are therefore of interest for developing further glaciomarine models (Puffett, 1974) and furthering understanding of this early stage in Earth's history. Data has been collected in five main study areas in an attempt to cover as much of the ancient continental margin as possible. The study areas include Espanola, Elliot Lake, Thessalon and Cobalt, Ontario and Marquette, Michigan. There are two glaciogenic formations in the Marquette area of Paleoproterozoic age, the Reany Creek Formation and the Enchantment Lake Formation. The Enchantment Lake Formation has been chronostratigraphically correlated to the Huronian Supergroup based on U-Pb age determination on detrital zircon, 2317±6 Ma, and diagenetic xenotime, 2133±11 Ma (Vallini et al., 2006). As these formations are present in such close proximity to each other, and there are no Archean glacial events recorded in the rest of the Canadian Shield, it is reasonable to correlate them with the Gowganda Formation, the thickest and most commonly preserved of the three Huronian glacial events.

Stratigraphic sections were compiled in each of the study areas and the sedimentary rocks were grouped into seven lithofacies associations (LA): 1) Planar Cross-Stratified Sandstone LA, 2) Basal Breccia LA, 3) Diamictite LA, 4) Interlayered

Siltstone and Fine-Grained Sandstone LA, 5) Slump LA, 6) Heterogeneous Sandstone LA and 7) Quartz-Rich Sandstone LA. These lithofacies associations likely represent a sequence of depositional environments on a shallow continental shelf. Initially, the shelf was dominated by what were likely large-scale, low-angle sandwaves, interbedded with successions of wavy bedding and possible hummocky cross-stratification indicating an open-water setting with tidal and storm processes reworking the sediments. The shelf then gradually evolved into an environment dominated by diamicite layers. The diamictite layers have dropstones as well as evidence of current activity indicating outsized clasts were likely being introduced into the environment as ice-rafted debris. Resedimentation events in the form of debris flows are thought to account for conglomeratic layers that are common in the Diamictite LA. The Interlayered Siltstone and Fine-Grained Sandstone LA, along with the Slump LA, seem to indicate deposition from suspension in a prodelta setting where large slump events are common. The gradual transition into a more sandstone dominated LA, with an abundance of current-related sedimentary structures, is indicative of the shallowing and coarsening upwards succession common to deltaic deposits. A final transition into the Quartz-Rich Sandstone LA indicates a return to a sandy, current-dominated open continental shelf environment with abundant tidally generated sedimentary structures such as herringbone cross-stratification. The Cobalt study area differs from this overall model in that evidence of grounded ice is present. Less exposure in the Marquette study area makes it difficult to draw overall conclusions on the evolution of the continental shelf but deposition in a subaqueous glacial outwash fan is hypothesized.

ACKNOWLEDGEMENTS

Most importantly, I would like to thank my thesis advisor Dr. Fralick for his patience and advice both in the field and with analysis of my data. His guidance has allowed me to achieve a goal that was most certainly daunting at first. Assistance was also provided by Anne Hammond, who generated petrographic thin sections, and Daniel LaFontaine, who assisted with field work. Dr. Hill is also to thank for helping to improve my presentation skills. I would also like to thank the geologists who took the time to join me in the field: Anthony Pace (OGS), Gary Grabowski (OGS), Dan Farrow (OGS) and Doug Duskin. In addition, Temex Resources Corp. is to be thanked for allowing me to look at their drill core. Finally, I would like to thank my family and friends for their continued support over the past two years.

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1. INTRODUCTION

The Huronian Supergroup consists of a southern thickening-wedge of Precambrian sedimentary deposits, dated at approximately 2.4 to 2.2 Ga, that span from Sault Ste. Marie, Ontario, along the north shore of Lake Huron and northward towards Cobalt, Ontario and Kirkland Lake, Ontario (Roscoe, 1969; Robertson, 1973; Frarey, 1977; Sims et al., 1980). The Supergroup is thought to have been deposited on what, at that time, was likely a divergent continental margin (Fralick and Miall, 1981; 1989). The Supergroup is divided into four stratigraphic groups. From oldest to youngest these groups are: the Elliot Lake Group, the Hough Lake Group, the Quirke Lake Group and the Cobalt Group (Fig. 1.2). The upper three groups consist of a cycle of conglomerates, which are thought to be related to glacial activity, overlain by mudstones, siltstones and sandstones (Bennet et al., 1991).

The rocks of the Gowganda Formation, on which this thesis will concentrate, record one of three glacial events preserved in the Supergroup containing distinct stratification and various types of bedding of interest for developing further glaciomarine models (Puffett, 1974). The Gowganda Formation has a very large area of exposure, which is not the case for all of the Formations in the Supergroup. Significant outcrops can be found spanning Ontario from Sault Ste. Marie to Sudbury and northward into the Cobalt and Kirkland Lake areas. The Gowganda is composed of a wide range of successions of diamictite, a poorly-sorted matrix-supported conglomerate, clast-supported conglomerate, poorly- to well-sorted sandstone, silstone and mudstone. The thickness of the Formation ranges from ~1070m near

Sault Ste. Marie, ~970-1150m in the Espanola area, ~950-2700m near Sudbury and ~700-1500m in the northern areas of exposure near Temagami, Cobalt and Kirkland Lake (Bennet et al., 1991). On a regional scale, the diamictite and conglomerates are more common in the basal portion of the Formation, whereas the upper portion is dominated by finer-grained sediments.

There has been much historical debate over the depositional origins of the Gowganda Formation. Subglacial, glacial-marine and glacialacustrine environments have all been proposed (Coleman, 1905a, 1905b; Ovenshine, 1965; Schenk, 1965; Casshyap, 1969; Lindsey, 1971; Young and Nesbitt, 1985; Legun, 1981; Miall, 1983, 1985; Mustard, 1985; Chandler, 1986). The important point to take away from these different interpretations is that there was indeed glacial influence during the deposition of the Formation. More specifically, the clast-supported conglomerates of the Gowganda have been interpreted to be a result of subaqueous debris flows (Miall, 1983; 1985) while the finer-grained upper portions of the Formation have been described as a prograding deltaic sequence (Rainbird, 1986; Junila and Young, 1995).

The purpose of this thesis is to investigate, on a regional scale, the sediments prior-, during- and post-Gowganda glaciation to gain a better understanding of the environments leading into and out of the glaciation. The overall goal is to gain a better regional understanding of the Paleoproterozoic ice margin ultimately placing the deposits of the Gowganda Formation into a clearer context.

This investigation was carried out by logging outcrops of the underlying Serpent Formation, the Gowganda Formation, and the overlying Lorraine Formation in five different study areas. The study areas are: the Elliot Lake area, the Espanola area, the area north of Thessalon, the Cobalt and Kirkland Lake area and the Marquette, Michigan area (Fig 1.1). The study areas were decided upon based on extensive exposure of the rocks, with the goal being to cover a large lateral extent of the Paleoproterozoic ice margin. Each study area was then broken down into lithofacies associations and large-scale correlations were attempted to relate similar environments in each area.

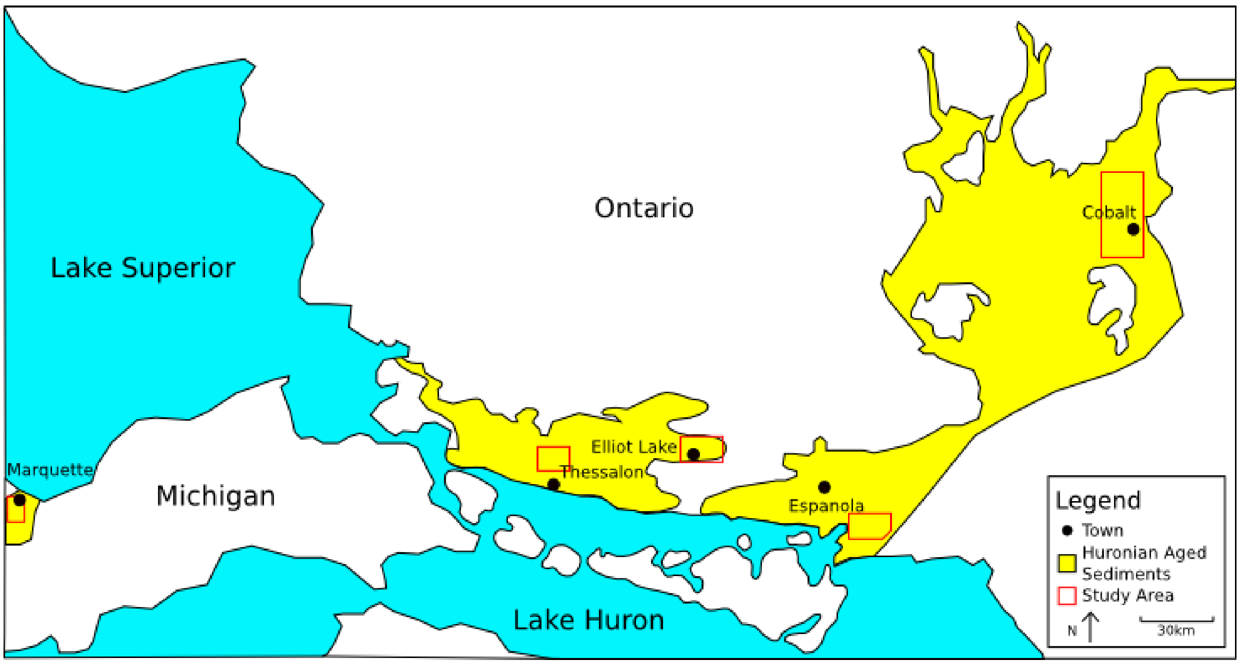


Figure 1.1 A map showing the locations of the study areas spanning the Paleoproterozoic ice margin.

The stratigraphic sections logged near Marquette, Michigan are part of the Enchantment Lake Formation in the eastern Marquette range and the Reany Creek Formation in the Dead River Basin. According to the mapping discussed in a United

States Geological Survey professional paper (Puffett, 1974), the sections identified as the Reany Creek Formation of the Marquette Range Supergroup are bound by Archean rocks. This Formation is often debated to be either Archean or Paleoproterozoic in age. The Reany Creek Formation is part of the Chocolay Group, located at the base of the Paleoproterozoic Marquette Supergroup. Vallini et al. (2006) constrained the depositional age of the Chocolay Group to 2300-2200Ma using detrital zircons and diagenetic xenotime. These deposits can then be correlated with the Huronian Supergroup in the Lake Huron region of Ontario, Canada (Vallini et al., 2006). As the Gowganda Formation is the thickest and most commonly preserved of the three Huronian glacial events, it is reasonable to assume it correlates to the Chocolay Group (Fig. 1.2).

The main depositional environments that will be discussed in this thesis include: glaciogenic environments, deltaic environments and off-shore marine environments.

Deposition in coastal glacial environments can occur in the terrigenous subglacial zone, near the grounding line, beneath an ice shelf as well as in the open ocean. In the terrigenous subglacial zone, deposition is below sea level but landward of the grounding line. Lodgement till is the common type of deposit found in this zone (Kellogg and Kellogg, 1988). The grounding line is situated at the border between grounded and floating glacial ice. The majority of submarine glacial deposition occurs in this zone. Subglacial and englacial streams enter the standing water, causing their velocity to decrease, which leads to deposition of a large amount of sediment by waning traction currents. These coarse-grained sediments, mainly gravels and sands, will often be deposited in the form of a subaqueous fan with the larger clasts being located nearer to the sediment source (Cheel and Rust, 1982; Powell, 1988, 1990). Ice shelves are connected to land based glacial ice and extend out over a water body.

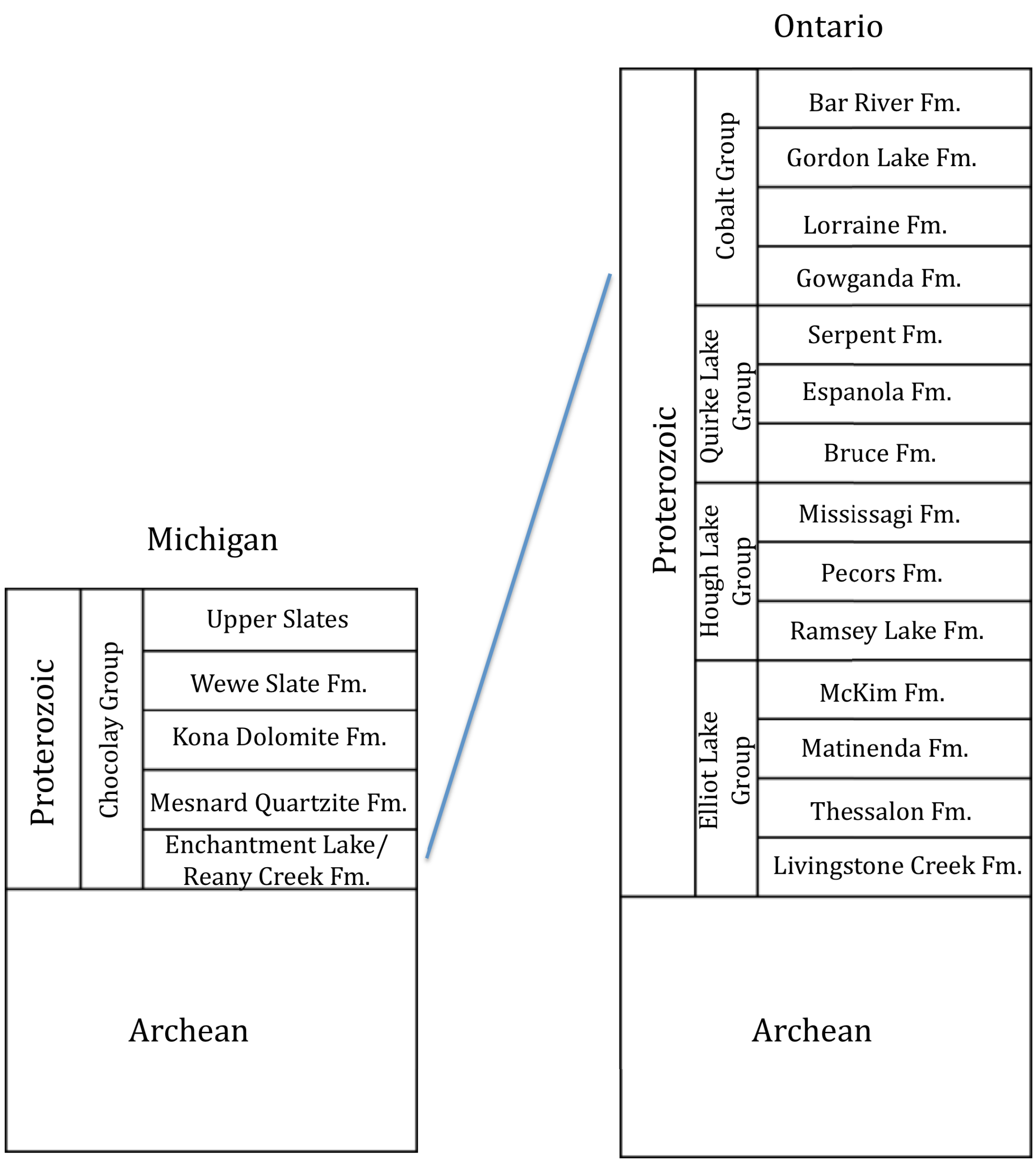


Figure 1.2 Stratigraphic tables showing formation and group names for Michigan and Ontario and the likely correlation between the two areas.

Comparatively less deposition occurs in this zone as the ice contains a lesser amount of sediment due to the large amount lost at the grounding line (Anderson et al., 1991). However, in some cases up to 1m of melting at the base of the ice shelf has been documented over the course of a year, depositing large amounts of sediment on the ocean floor (Thomas, 1979). A decreased rate of deposition also provides time for the bottom currents to sort and winnow sediments in this area (Miller, 1996). In the open ocean, glacial sedimentation occurs as intermittent interruptions in normal marine deposition. The release of iceberg-rafted debris will cause isolated clasts and dumps of clasts within the marine sediments (Thomas and Connell, 1985). Icebergs are also capable of scouring and reworking marine sediments (Barnes and Lien, 1988).

The deposition in deltaic environments outlined in this thesis is likely occurring in an inner shelf river delta system. These types of deltas can be moderate to large-scale deltas that build out onto the continental shelf (Reading and Collinson, 1996). The deltaic environment is divided into three zones: the delta plain, the delta front and the prodelta. Two of the three environments are discussed in this thesis. The prodelta, usually the deepest environment, is the portion of the delta that is dominated by sedimentation from suspension. It is generally unaffected by wave action or tidal processes (Reading and Collinson, 1996). The prodelta is composed of laminated silts and mud with periodic graded beds that usually represent sediment-ladened flood events eminating from the sediment source (Reading and Collinson, 1996). The delta front is defined as the portion of the delta where fluvial and basinal processes interact. At the river mouth, the flow enters the open water and expands both laterally and vertically, decreasing the velocity and ultimately depositing the sediment being carried

(Reading and Collinson, 1996). This area is usually composed of the distributary mouth bar and the distal bar deposits. The distributary mouth bar is located nearer the sediment source and is commonly composed of sand beds separated by thin mud layers. The distal bar sediments are an intermediate zone between the sand dominated environment of the distributary mouth bar and the silt and mud dominated prodelta. Ripples to small trough cross-stratification are common in these environments. Deformation processes are common in the prodelta and delta front due to high rates of deposition and highly water-saturated sediments (Coleman et al., 1983; Lindsay et al., 1984; Coleman, 1988).

The final depositional environment discussed in this thesis is the off-shore zones of shallow, clastic seas. The sandstone units commonly deposited in these environments are differentiated as being tide-dominated or storm-dominated but are preserved in close association (Johnson and Baldwin, 1996). Sedimentary features that are commonly used to distinguish these environments include: high textural and mineralogical maturity, a lack of mudstone, considerable lateral extent, tidal cross-bedding, mud-drapes or layers in the tide-dominated environments and the presence of wave ripple laminations and hummocky cross-stratification in the case of the storm-dominated environments (Johnson and Baldwin, 1996).

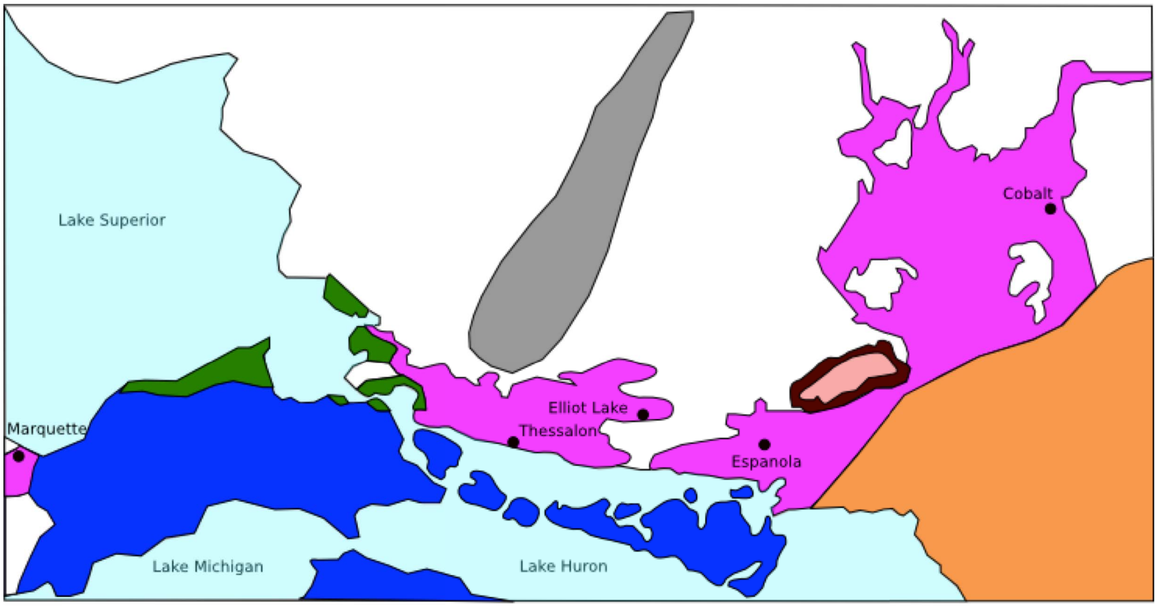
The following chapters will outline how these environments are related on the Paleoproterozoic ice margin of the Gowganda Formation.

2. **REGIONAL GEOLOGY**

The Huronian Supergroup is a wedge of Paleoproterozoic sedimentary and minor volcanic rocks, approximately 2.4 to 2.2 Ga, located along the southern edge of Ontario's portion of the Canadian Shield. The Supergroup spans from the Sault Ste. Marie region in the west, along the northern shore of Lake Huron to Sudbury and northeast towards the Cobalt and Kirkland Lake regions. At its thickest, the wedge reaches up to 10km in the Lake Huron region (Card et al., 1973; Miall, 1985). These rocks were deposited on what was thought to have been at that time a divergent continental margin (Fralick and Miall, 1981; 1989).

The Supergroup is divided stratigraphically into four groups. From oldest to youngest the groups are as follows: the Elliot Lake Group, the Hough Lake Group, the Quirke Lake Group and the Cobalt Group. The Elliot Lake Group is composed of volcanic as well as sedimentary rocks and is well known its uranium deposits. The other three groups are composed of sedimentary rocks, which follow a general cycle in which a conglomerate formation is stratigraphically overlain by mudstone, siltstone or carbonate formation, which is then topped by a sandstone formation (Roscoe, 1969). The Quirke Lake Group contains the lone member of calcareous sedimentary rocks, the Espanola Formation, within the entire Supergroup.

The sedimentary rocks of the Huronian are thought to have been deposited by glacial, fluvial and shallow marine processes (Miall, 1985). The paleocurrents preserved in these formations indicate the source area of the sediments was likely located to the north with a general southward transport direction (e.g., Long, 1976,



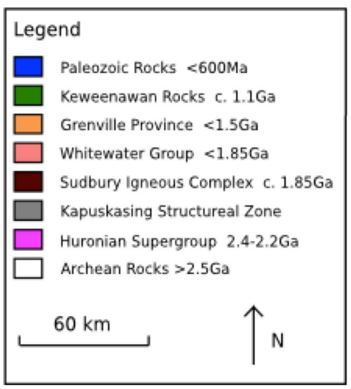


Figure 2.1. Regional geology of the study area with the Huronian Supergroup in pink spanning the North Channel of Lake Huron up to the Cobalt area in the east. Parts of the Huronian Supergroup, more specifically the Gowganda Formation, are correlated to rocks in the Marquette, Michigan area in this thesis (modified after Eyles and Miall, 2007).

1978; Theis, 1979; Fralick and Miall 1989; Miall, 1985; Rice, 1987, 1988; Debicki, 1990).

Historically, the Huronian Supergroup was mined for uranium deposits in the Elliot Lake region but deposits of silver, cobalt and copper are present as well and are associated with igneous intrusions in the sedimentary rocks (Bennet et al., 1991).

The Huronian Supergroup is dated between roughly 2450 Ma and 2219 Ma (Bennet et al., 1991). The Copper Cliff Formation, a volcanic sequence near the base of the Elliot Lake group, interfingers with the sedimentary rocks of the Huronian. A rhyolite within this sequence has been dated at 2450±25 Ma providing the older age constraint (U-Pb zircon, Krogh et al., 1984). The younger age constraint is provided by the Nipissing diabase intrusions which intrude the Supergroup (Van Schmus, 1965; Fairbairn et al., 1969). These tholeiitic gabbro sills and dykes have been dated at 2219±4 Ma (U-Pb baddeleyite, Corfu & Andrews, 1986).

Also of interest is a general lack of red coloured rocks and clasts in the Huronian prior to their appearance in the Gowganda Formation, which is thought to be an indication that deposition of the Supergroup was occurring prior to, during and after the Great Oxidation Event. An oxygen-deficient atmosphere would cause the reduction of Fe_2O_3 to FeO effectively eliminating red-coloured weathering (Roscoe, 1969, 1973; Frarey and Roscoe, 1970). This could also account for the preservation of detrital uraninite and pyrite during deposition of the sedimentary rocks of the lower Huronian Supergroup.

Structurally, the rocks of the Huronian Supergroup are bounded by the Archean Superior Province to the north, which they onlap (Bennet et al., 1991). The Grenville Tectonic Front borders the southeast (Easton, 1992) and Lake Huron and areas of Paleozoic sedimentary rocks lie to the south (Bennet et al., 1991). The rocks of the Huronian Supergroup between Sault Ste. Marie and Sudbury have been subjected to the Penokean Orogeny dated between 1.86 Ga and 1.83 Ga (Cannon, 1973; Hurst and Farhat, 1978; Medaris, 1983; Bickford et al., 1986; Hoffman, 1989). This area is now composed of large regional, east-trending folds and faults referred to as the Penokean Fold Belt. This orogeny resulted in low-grade metamorphism for the most part, but some amphibolite facies mineral assemblages are present to the west of the Sudbury region (Bennet et al., 1991).

In the Cobalt and Kirkland Lake regions, the Gowganda Formation is divided into the lower Coleman Member and the stratigraphically higher Firstbrook Member (Mustard and Donaldson, 1987a). In this area, the Gowganda Formation stratigraphically overlies the igneous and metamorphic rocks of the Archean and is separated by an angular unconformity (Mustard and Donaldson, 1987a). This unconformity surface dips at approximately 30° with the majority of the layers in the Coleman Member paralleling topographic highs (Mustard and Donaldson, 1987a). The Cobalt Group as a whole, has been subjected to very little deformation other than normal faults and large open folds, which occurred to the formations underlying the Gowganda Formation (Card et al., 1973; Dressler, 1977). Allowing for this folding, the paleotopography of the area is thought to have been less than 100m and dominated by broad shallow troughs (Mustard and Donaldson, 1987a).

In northern Michigan, there are three areas of glaciogenic deposits of the Chocolay Group. These include the Fern Creek Formation in the Menominee Range, the Enchantment Lake Formation in the eastern Marquette range and the Reany Creek Formation in the Dead River Basin (Vallini et al., 2006). These three glacially related formations are often correlated (Gair and Thaden, 1968; Young, 1973; 1983; Ojakangas, 1982, 1985). The Reany Creek Formation is often suggested to be of Archean age being as it is fault-bounded on all sides by Archean rocks. However, it seems more plausible to correlate the Reany Creek Formation with the Paleoproterozoic Formations as there is no known Archean glaciation in the area. Similar reasoning can be applied to correlate the rocks studied for this thesis in the Marquette, MI region to those of the Gowganda Formation. The Gowganda Formation is the thickest and most widely preserved of the glacially-related formations of the Paleoproterozoic Huronian Supergroup making it very likely that the glacially-related rocks in the Marquette area were deposited during the same glacial event.

3. ESPANOLA STUDY AREA LITHOFACIES ASSOCIATIONS

A map of the Espanola study area with the locations where outcrops were logged to compile data is shown in Figure 3.1. Three stratigraphic sections were logged in the Espanola study area, two on McGregor Bay and one on Iroquois Bay all of which are southeast of the town of Espanola, Ontario. Each of these general stratigraphic columns for the area is shown in Figure 3.2. Data for the following lithofacies descriptions were compiled from these study locations.

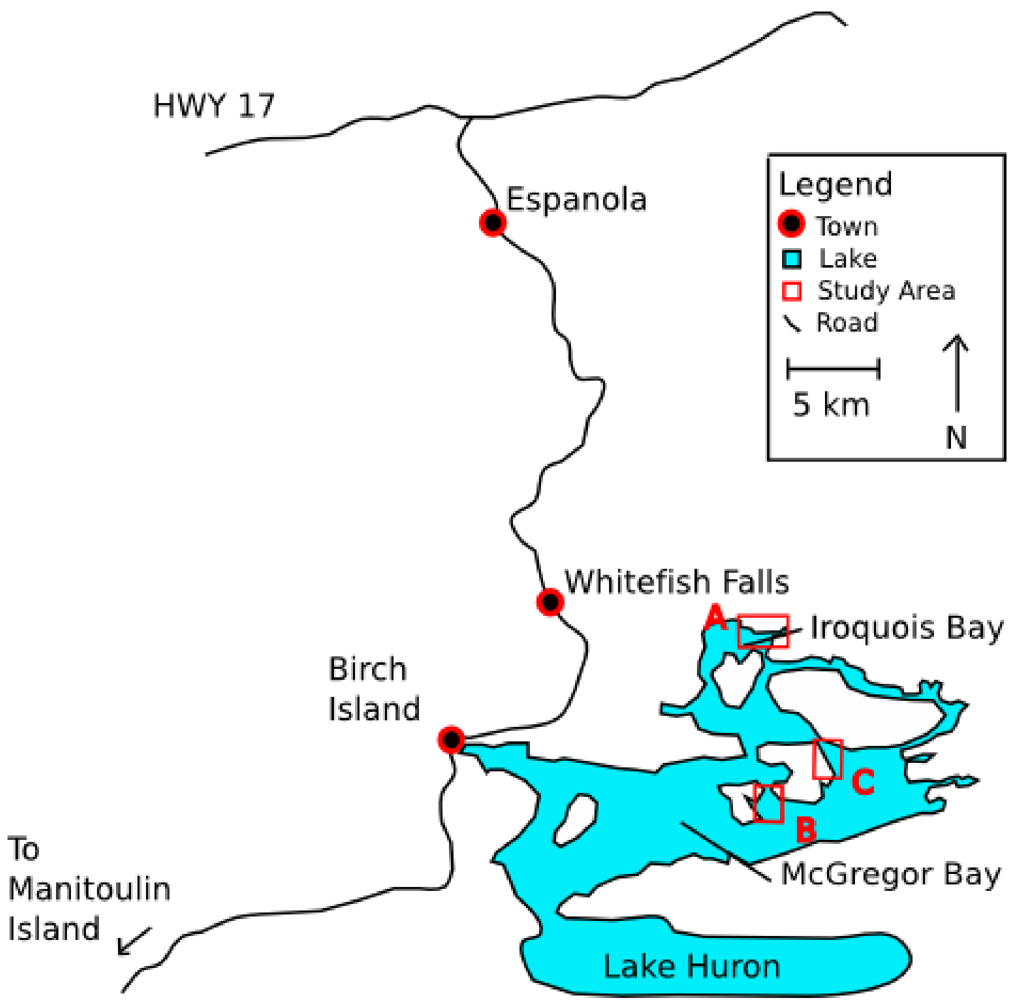


Figure 3.1 A map of the Espanola study area showing the locations of the three stratigraphic columns that were logged, two on McGregor Bay and one on Iroquois Bay all of which are southeast of the town of Espanola, Ontario.

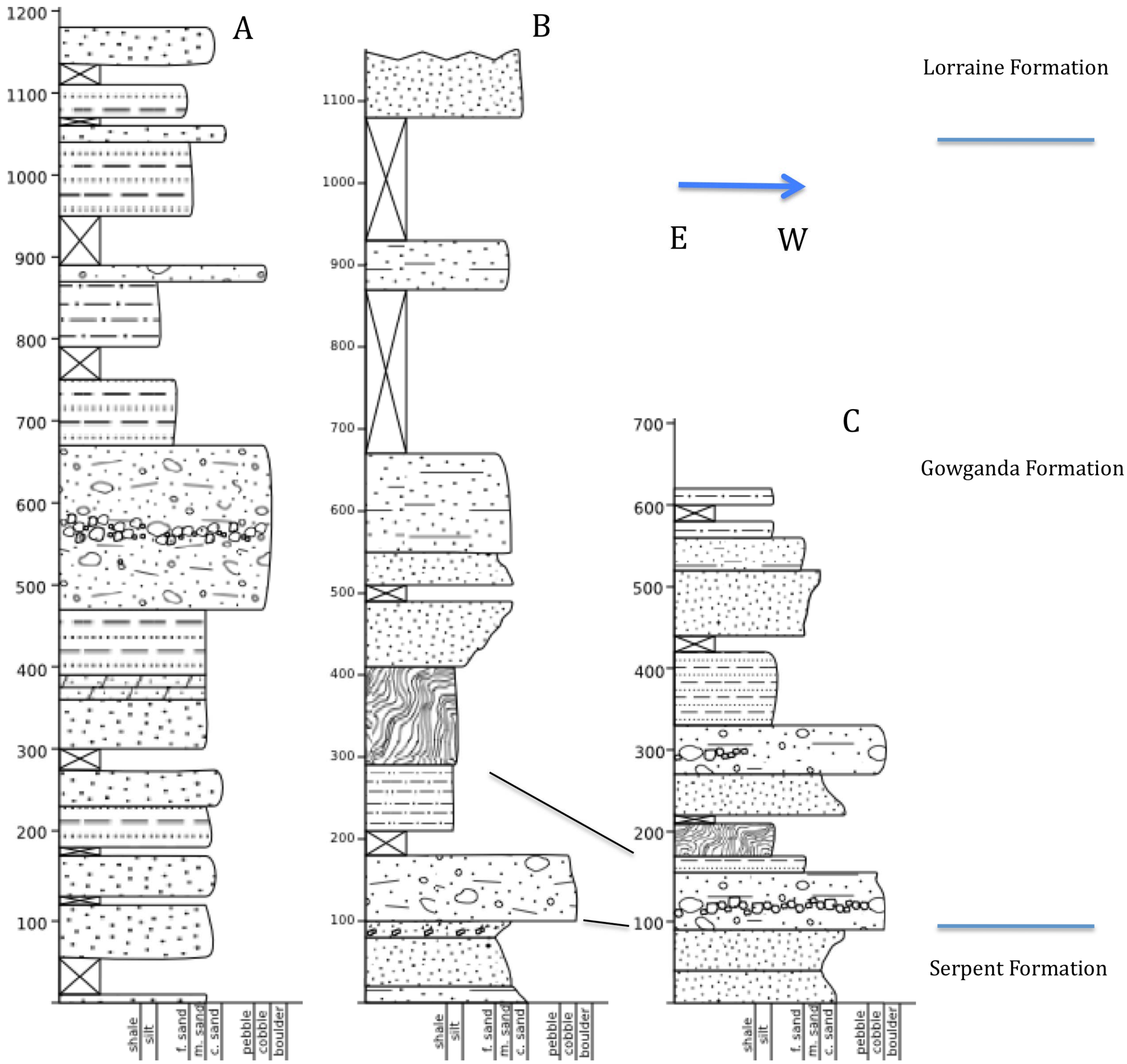


Figure 3.2 A) A stratigraphic column from the north limb of the anticline in Iroquois Bay. B) and C) Stratigraphic columns from the southern limb of the anticline, on McGregor Bay, that are correlated using the base of the first succession of the Diamictite LA and the as well as the base of the Slump LA. The scale is in meters for all of the columns (see legend in Fig. 3.2D on next page).

Legend

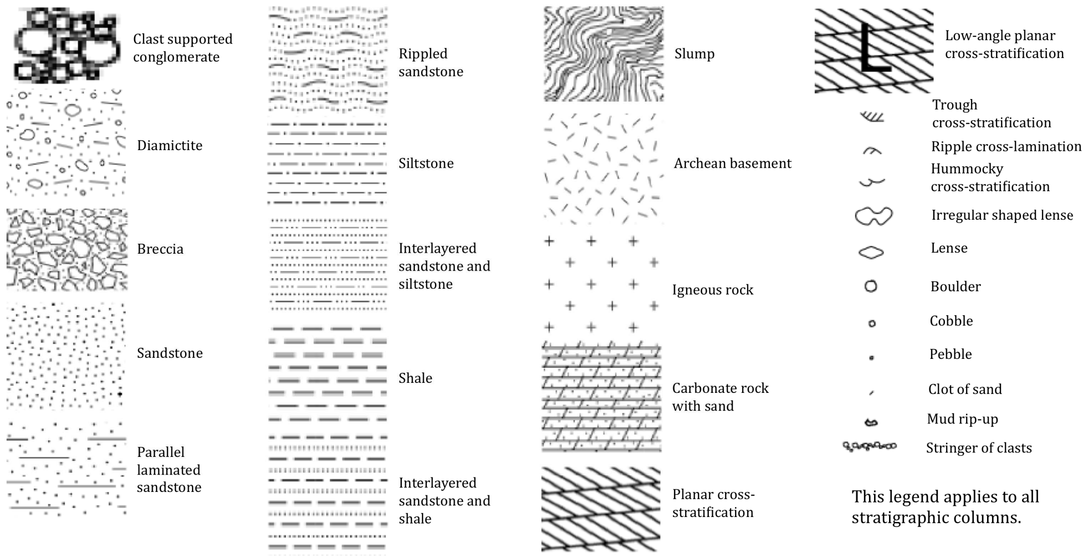


Figure 3.2 D) The legend that applies to all of the stratigraphic columns in this thesis.

3.1 Planar Cross-Stratified Sandstone Lithofacies Association

This lithofacies association (LA) was predominantly located in the upper portion of the Serpent Formation beneath the Diamictite LA of the lower Gowganda Formation. A detailed stratigraphic column of the LA, compiled in the McGregor Bay region, is shown in Figure 3.3.

The most prevalent layers and lenses in this LA are those of medium-grained sand generally with low angle planar cross-stratification dipping between 5° and 10° (Fig. 3.4A). These sandstone layers range from 40cm to 5m thick, averaging approximately 1.8m thick. In a few cases, planar cross-stratified lenses erosively cut down into each other and range from 0.15 to 1.3m thick and 2 to 6m long where visible. In some cases the angle of repose seems to increase slightly upwards in the

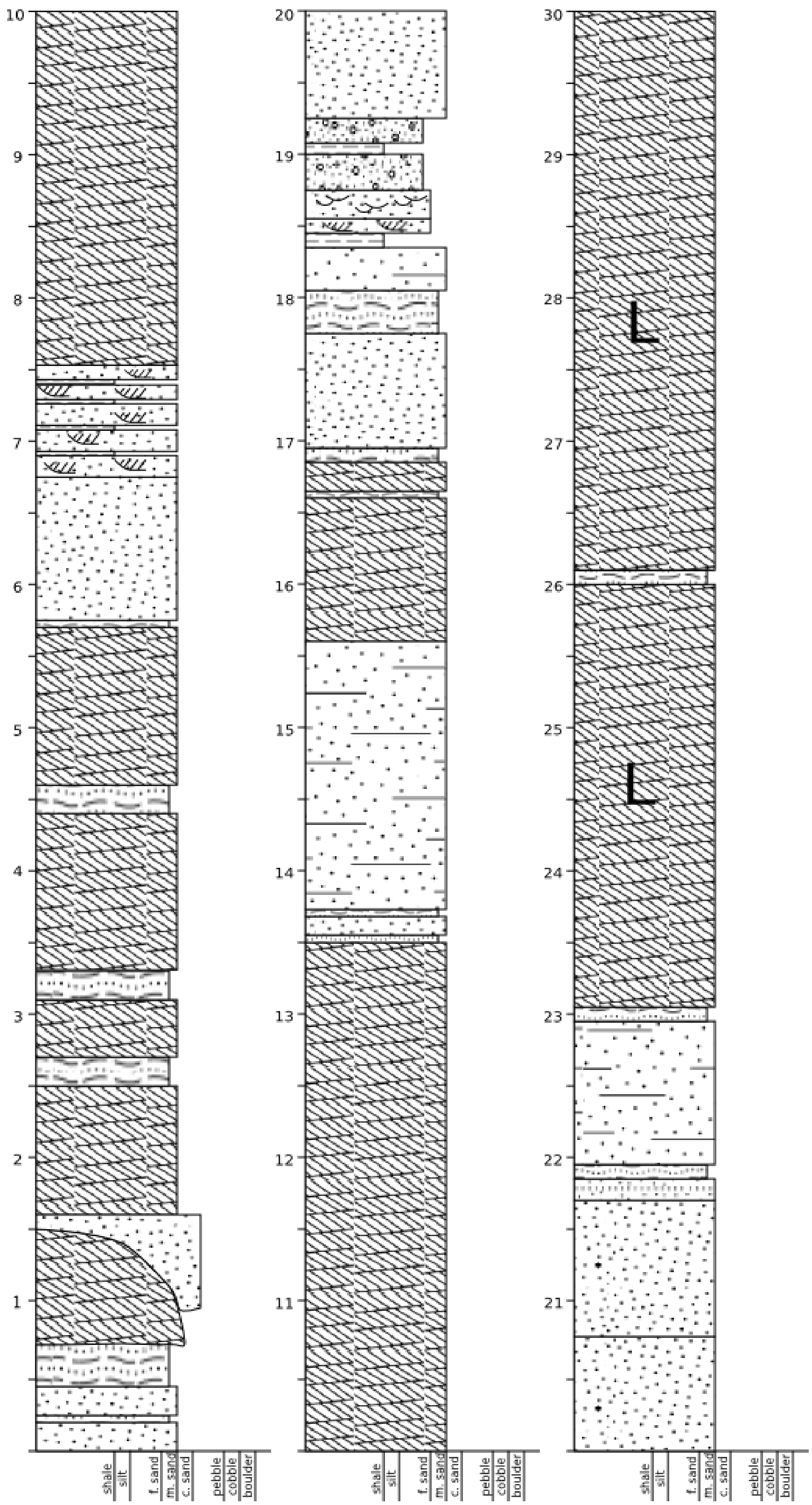
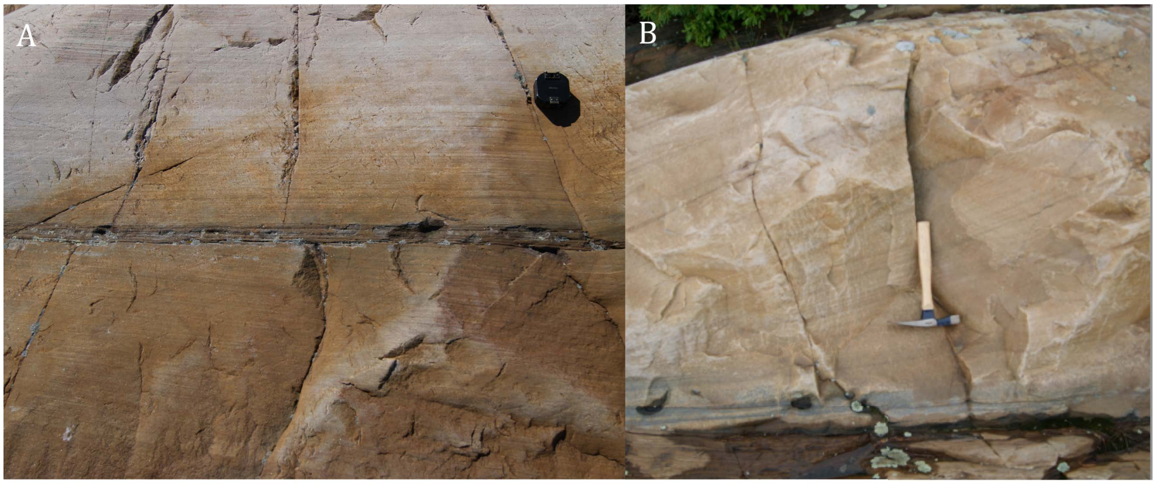


Figure 3.3. A detailed stratigraphic colunm of the Planar Cross-Stratified Sandstone LA from the McGregor Bay region, southeast of Espanola, ON (scale in meters).

layers (Fig. 3.4B) and on one occasion a 2.6m thick layer contained planar cross-stratification dipping at approximately 20-25°, a much higher angle of repose. In higher-angle planar cross-stratifications, thin, 1 mm thick, shale flasers are present at the base of the stratifications (Fig. 3.4B). Rare lenses of very coarse-grained sand 1 to 3cm thick and 10 to 20cm in length are found within the planar cross-stratified layers. In some cases the layers or lenses have a succession of sedimentary structures. Most commonly, the basal ¾ of the sandstone layers were parallel laminated while the upper ¼ were planar cross-stratified dipping between 15° and 20°. Some horizons of current ripples are found within the thicker sandstone layers. In some cases, these current ripples are present in the upper portion of the layers showing evidence of sediment reworking. Paleocurrent measurements obtained from these layers are shown in a rose diagram in Figure 3.4C and provide a strong trend for paleocurrents to the west with minor trends to the northwest and southeast.

Medium- to coarse-grained massive sandstone layers 10cm to 2.2m thick, averaging 54cm, are commonly associated with the planar cross-stratified layers. These sandstone layers often have lenses of very coarse-grained sand 1 to 7cm thick and 5 to 47cm in length dispersed throughout them. In addition, 1 to 3mm thick shale layers are often present between the massive sand layers. These shale layers increased in abundance up section approaching the Gowganda Formation. In some cases, mud rip-ups 1mm to 1cm thick and 1 to 4cm long are present. These rip-ups are generally confined to the bottom portion of the massive sand layers aligned parallel to bedding and very rarely are aligned at high angles to bedding.



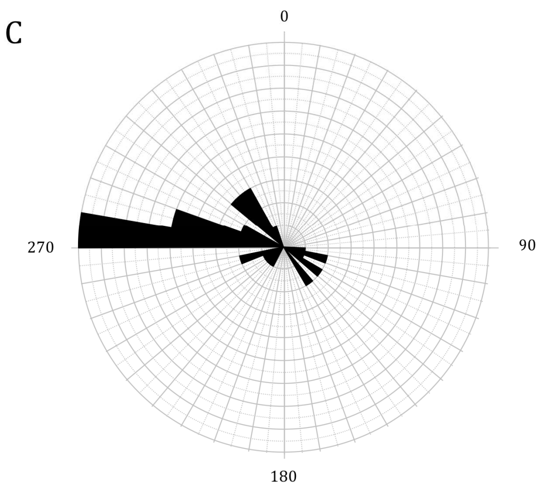


Figure 3.4. A) Two beds with large-scale low-angle planar cross-stratification separated by a thin shale layer. B) The angle of the cross-stratification increasing upwards in a sandstone layer. Shale flasers are more common at the base of the stratification. C) A rose diagram compiling 37 paleocurrent measurements taken from the Planar Cross-Stratified Sandstone LA provides a strong trend for paleocurrents to the west with a minor trends to the northwest and southeast.

Less commonly, fine- to medium-grained parallel laminated sandstone layers that range from 20cm-2.2m thick and average 1.1m are found within this LA (Fig. 3.5A). The previously described lenses of coarse-grained sand are also found within these layers.

Thinner successions, 2 to 100cm thick that average 17cm, of interlayered fine- to medium-grained sandstone and shale are regularly found interlayered with the larger layers of planar cross-stratified, massive and parallel laminated fine- to coarse-grained sandstone. Within these thinner successions, the sand layers are 0.3 to 4cm thick while the shale layers are 0.1 to 0.7cm thick. The sand layers occasionally have ripple cross-laminations with thin, 1mm thick mud flasers, and are draped by the thicker shale layers. The contacts between the two are sharp but irregular with the sand often loading into the shale. Overall, these layers take on a wavy bedded appearance (Fig. 3.5B). One 80cm thick layer of lenticular bedded coarse-sand lenses in shale that coarsened upwards to wavy, followed by flaser bedding near the top of the layer was logged within this LA. In the northern section on Iroquois Bay, a few occurrences of wavy to flaser bedding were documented. Within these successions, the sand layers are 1 to 4cm thick while the shale is 3 to 4mm thick and 2 to 4cm long where it is present as lenses.

Six layers of fine-grained sandstone averaging 13cm in thickness are found within this LA containing small-scale low-angle truncations indicative of hummocky cross-stratification. The top of the layers usually contained symmetrical bifurcating wave ripples with thin 1mm thick shale layers draping the laminations (Figs. 3.5C and D).

Examples of soft-sediment deformation are also present within the sandstones of the Serpent. Two layers, 13cm and 23cm thick respectively, are present with rounded pseudo nodules ranging from 1 to 8cm long and 0.7 to 3cm thick of fine sand within a very fine sand matrix (Fig. 3.6A). These structures are concave up indicating they loaded into the finer-grained matrix.

Siltstone layers are uncommon within the planar cross-stratified sandstone LA. Only three layers were documented 80cm, 140cm and 400cm thick. Rare layers of fine- to medium-grained sandstone 0.1 to 5cm thick or lenses of fine- to medium-grained sandstone 0.3 to 1cm thick and 2 to 7cm in length were found within the siltstone.

Figure 3.5 A) Parallel laminated fine- to medium-grained sandstone layers. B) Wavy bedded ripple cross-laminated sand and shale. C) Wave ripple cross-laminations. D) The top of a bedding plane with symmetrical bifurcating wave ripples.

Shale layers within the LA range from 0.1 to 75cm thick and average 15cm. Rare layers of mud-rich, fine-grained sandstone 0.1 to 10cm thick are present within the shale. In two locations, what appear to be injections of medium- to coarse-grained sandstone containing rip-ups of shale were documented. The rip-ups range from 0.5 to 5cm thick and 1 to 12cm in length and are generally aligned with a preferred orientation parallel to bedding. The contacts between the injecting sand and the sand that is rich in rip-ups are sharp but irregular.

Lastly, in the northern section logged on Iroquois Bay, layers of dolomite were documented. The layers range from 1.05 to 11m in thickness and are commonly lense-shaped, thinning significantly to 10 to 40cm where visible. In one case, the dolomitic layer contained lenses of medium-grained sandstone 20cm thick and 1.6 to 2m in length (Fig. 3.6B).

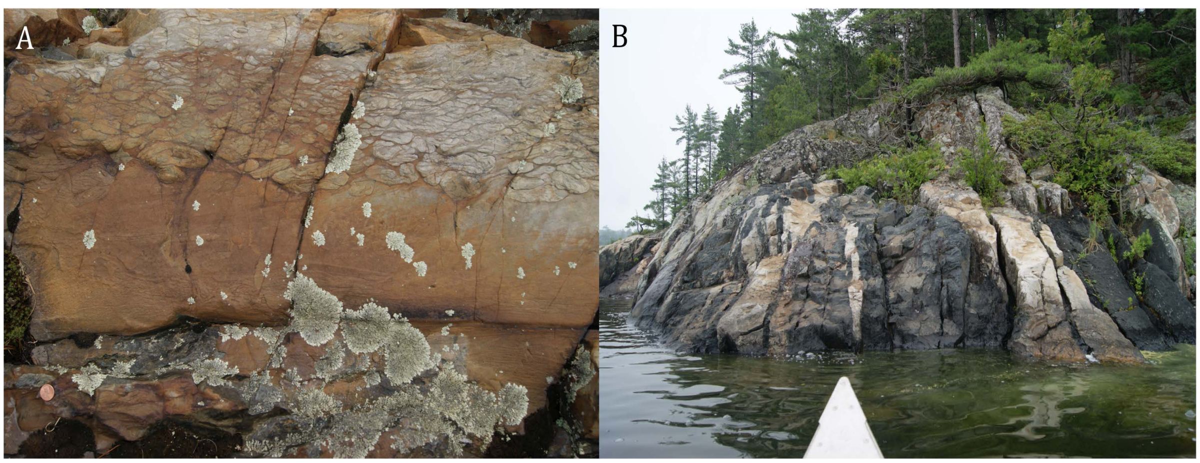


Figure 3.6. A) Rounded pseudo nodules of fine-grained sand in a very fine-grained matrix shows an example of soft sediment deformation. B) Lenses of dolomite (black) interbedded with the sandstone (white) of the upper Serpent Formation.

3.2 Diamictite Lithofacies Association

The diamictite layers that compose the majority of this LA have a mud-rich siltstone matrix with fine- to very coarse-grained sand dispersed throughout. The layers of diamictite range from 10cm to approximately 175m thick with an average thickness of 7.8m. A representative stratigraphic column compiled in the McGregor Bay area is visible in Figure 3.7.

Outsized clasts within these layers are granule- to boulder-sized, the largest reaching 150cm in diameter. They are subangular to subrounded and predominantly of granitic composition. In the northern section on Iroquois Bay, cobble- to small boulder-sized clasts of nearly pure quartz are also present. These outsized clasts are often distributed non-uniformly throughout the matrix (Fig. 3.8A) or can be arranged as lag deposits 3 to 15cm thick (Fig. 3.8B), as stringers one clast thick or as lenses. The lenses are clast supported with a coarse-grained sand matrix and generally measure 30 to 38cm in length and 2cm thick. The diamictite also has lenses of fine- to very coarse-grained sand within the matrix (Fig. 3.8B). These lenses can be small, 0.5cm thick and 2cm long, or can appear to be attempts at layers within the diamictite and measure 40cm thick and 5 to 10m long. The contacts between these lenses and the matrix can be sharp or whispy and gradational. In contrast to these clast-rich areas, the diamictite matrix also contains horizons of cleaner mud-rich matrix with no little to no outsized clasts. In some cases, laminations of very fine-grained sand and mud, 2 to 5mm thick, are visible in these horizons and when they are present can be badly contorted or compressed by an outsized clast.

Conglomeratic layers composed of rounded, granitic granules to cobbles in clast-support are also common within this LA. The matrix of these layers is a mud-rich fine-grained sandstone. The conglomerate is generally found as layers and lenses 95 to 200cm thick, averaging 120cm, and 9.5 to 20m long. In one case, a clast-supported conglomeratic lense has a flat bottom and curved upper surface taking on a mound-shape instead of the traditional flat top and curved lower surface of a lense. The contacts between the conglomerate and the diamictite are sharp (Fig. 3.8C) and in

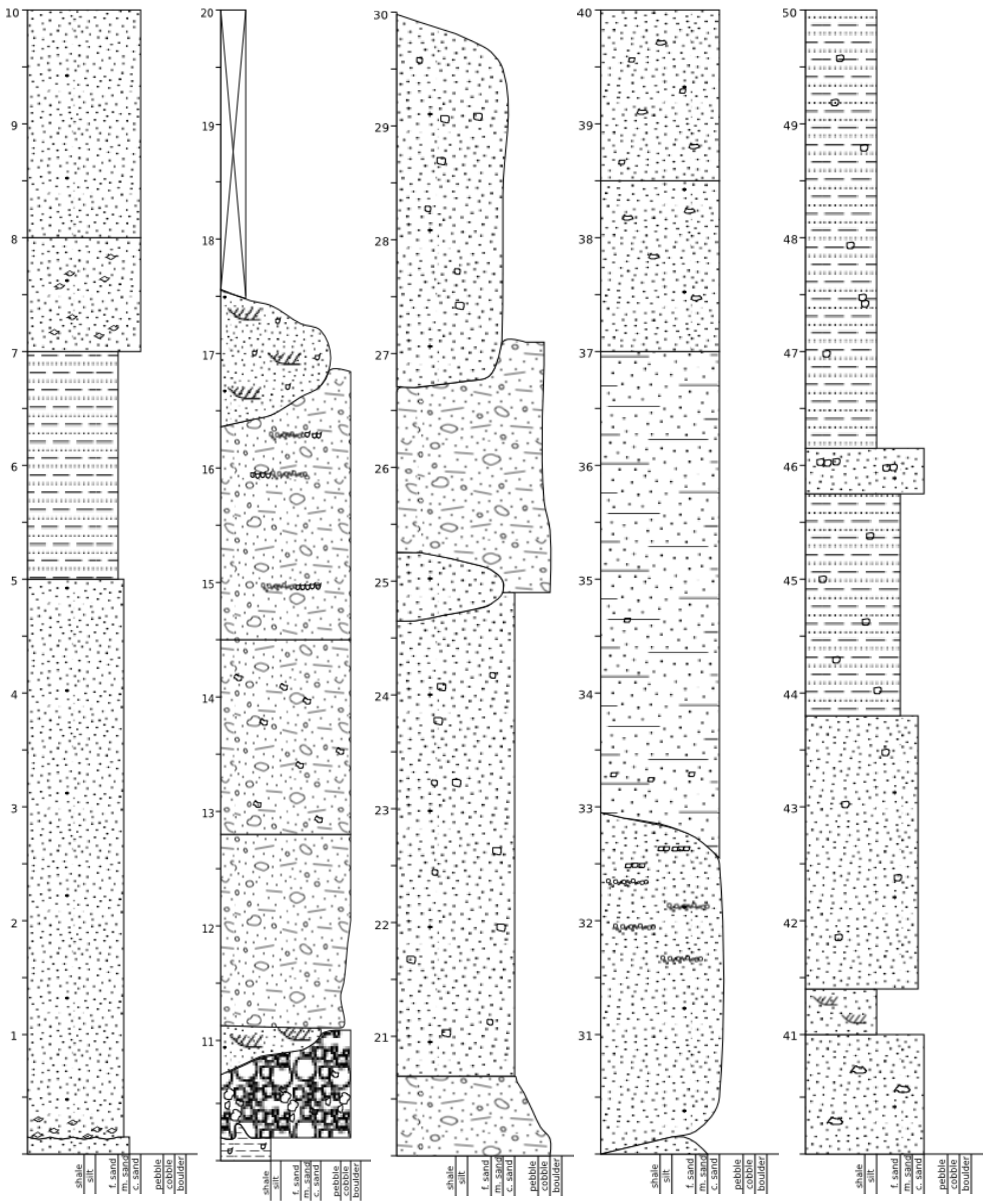


Figure 3.7 A detailed stratigraphic column of the Diamictite LA of the Espanola study area compiled in McGregor Bay (scale in meters).

one location a layer of conglomerate is found laterally abutting a diamictite layer, which likely indicates an erosive contact. In a couple of cases, the mud-rich matrix of the diamictite injected itself into the overlying clast-rich layer. In addition to the granitic clasts, angular rip-ups of contorted mud are common in these layers (Fig. 3.8D). In some of the clast-rich layers, intensely weathered carbonate clasts are common. These are visible as the eroded empty holes in Figures 3.8C and D. The layers are most often graded from cobbles to small pebbles and granules (Fig. 3.8C) but can also be inverse graded in the basal portion of the layer. They are not as common nor are they as thick as the diamictite layers but they do generally occur interlayered with them.

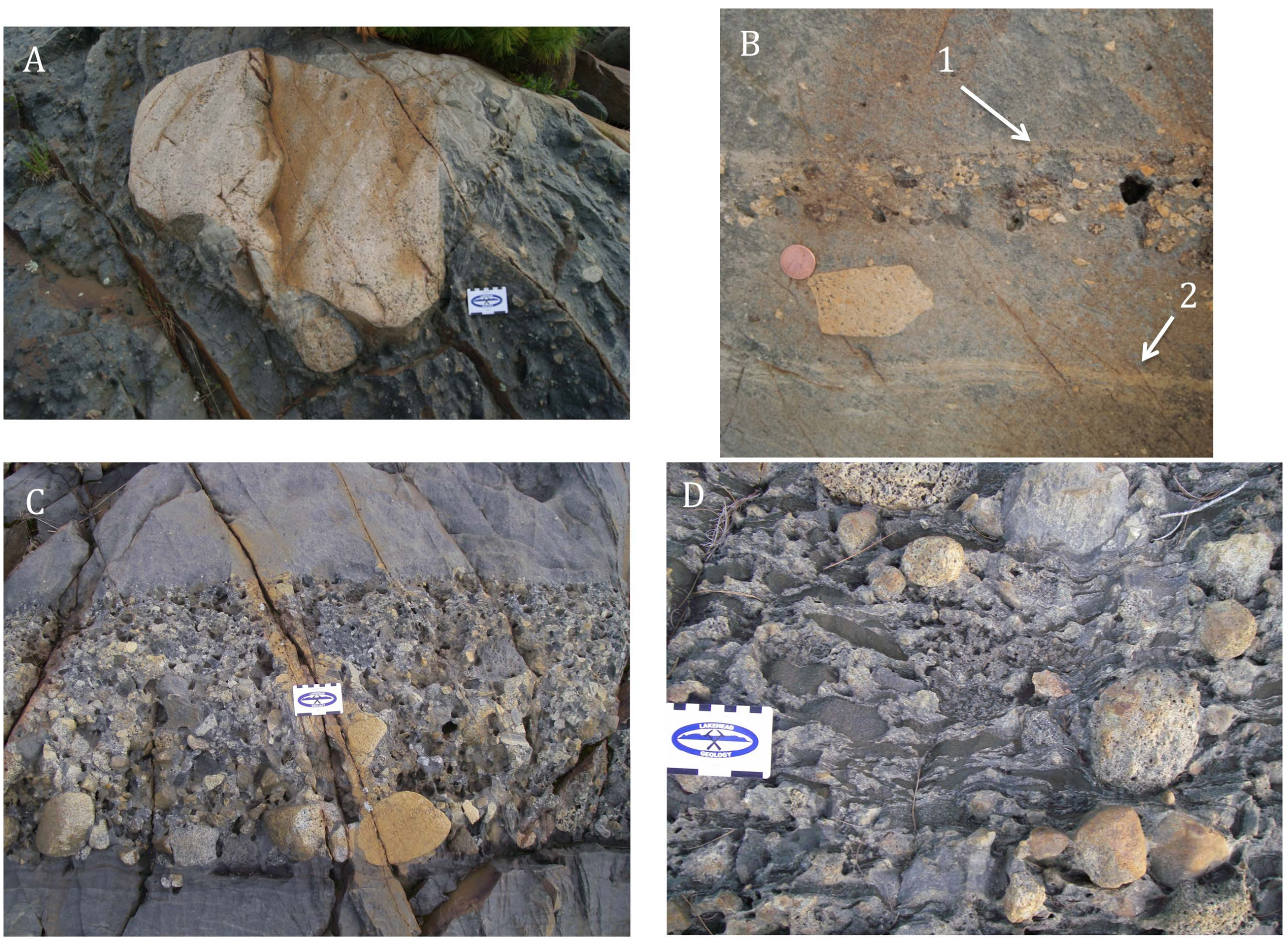


Figure 3.8 A) Outsized clasts distributed non-uniformly throughout matrix. B) A lag deposit of outsized clasts (1) in the diamictite matrix. Whispy sandstone lenses present at the base of photo (2). C) Clast-supported conglomerate layer with sharp contacts and normal grading from cobbles to small pebbles and granules. The empty holes in the layer are where the carbonate clasts were before they were eroded away. D) Angular rip-ups of contorted mudstone common in conglomerate layers.

The transition into the Gowganda Formation is a gradual one with the appearance of layers of diamictite and conglomerate, which are interbedded with massive, parallel laminated, low-angle planar cross-stratified (Fig. 3.9A), trough cross-stratified (Fig. 3.9B) and graded sandstone as well as rare siltstone layers. In the basal portion of the western section, paleocurrents of 040° and 050° were obtained from low-angle planar cross-stratifications. The contacts between the sandstone and diamictite layers are sharp but irregular with scalloped-shaped scours and lenses of sand often cutting down into underlying layers of diamictite. The contacts between sandstone and overlying conglomeratic layers are erosive with scours into the upper portion of the sand. In some cases, the outsized clasts in the diamictite load into the tops of the underlying sandstone layers also causing irregular contacts. There are rare gradational contacts between sand layers and overlying diamictite layers. In the eastern section logged on McGregor Bay, a contact between sandstone and the overlying diamictite layer near the base of the Gowganda consists of a downward "V" 40cm deep and 20cm wide cut into the sandstone. The "V" is filled with clasts some of which are oriented vertical to bedding. The bottom 10cm are more clast-rich with larger clasts from 0.3 to 3cm while the upper portion is more sand-rich (Fig. 3.9C).

Upsection in the lithofacies association, sandstone layers that are generally more clay-rich than those of the Serpent Formation become common. These sandstone layers can be massive or they can have a range of structures in them including grading

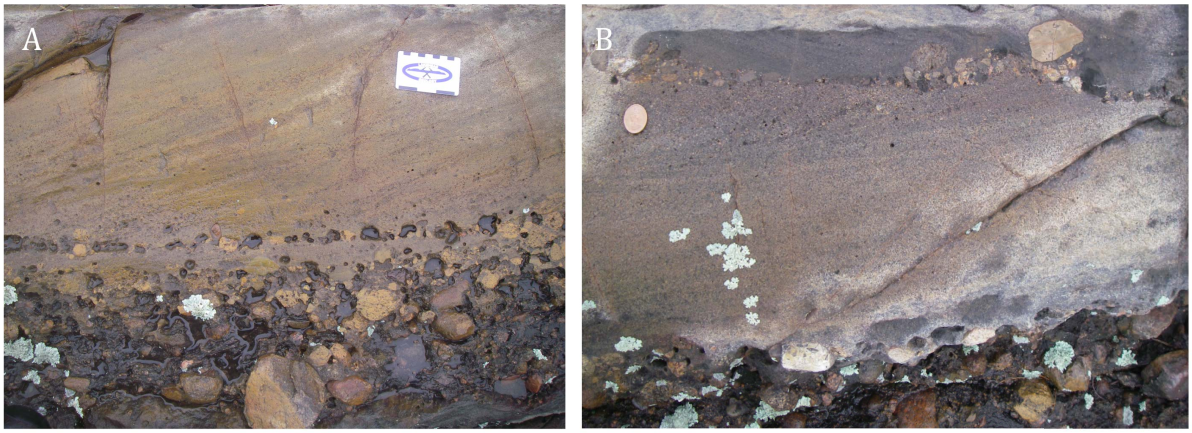


Figure 3.9 A) Planar cross-stratified sandstone layer interbedded with a conglomerate layer. B) Trough cross-stratified sandstone layer interbedded with a conglomerate layer. C) A contact between a sandstone and an overlying diamictite layer consisting of a "V" shape filled with some vertically oriented clasts.

from very coarse to fine sand and parallel laminations predominantly at the base of layers that are commonly overlain by wave ripples. Some of the layers also appear to have some possible hummocky cross-stratification. The laminations are accentuated by thin, 1mm thick, mud drapes. Nearing the top of the LA, small, 5 to 10cm thick, climbing dunes were also documented as well as small-scale trough cross-stratification (Fig. 3.10A) with occasional outsized clasts 1 to 4cm in diameter on the set boundaries (Fig. 3.10B). The sandstone occurs as layers 7cm to 6m thick averaging 1.2m or as large lenses 25cm to 1.4m thick and 3 to 20m long with both parallel laminations and current ripples, that erosively cut down into underlying diamictite layers (Fig. 3.10C). These layers range in composition from fine- to very coarse-grained sand and commonly have rounded to subrounded outsized clasts of granite, 0.3 to 20cm in diameter, concentrated in the upper 5 to 22cm of the sandstones. Mud rips-ups are commonly present as well, aligned parallel to bedding or in the case of the coarser sand, rip-ups of fine- to medium-grained sand. In some cases, the outsized clasts within the sandstones form lenses up to 15 to 30cm thick and 2m long or stringers that are one clast thick. Rare grading is present within the lenses from small pebbles and

Figure 3.10 A) Small-scale trough cross-stratification, an example of one of the many sedimentary structures present in the sandstone layers of the upper Diamictite LA. B) Outsized clasts still present in the sandstone layers (1). C) Sandstone layers near the top of the Diamictite LA that commonly cut down into underlying diamictite layers.

granules to coarse sand. Where laminations are present, the granitic clasts are found compressing them (Fig. 3.11A) and in one case an erosive scour is present adjacent to the outsized clast with deposition occurring on the other side (Fig. 3.11B). This is evidence for the presence of a paleocurrent.

Rarely associated with the Diamictite LA are successions of interlayered clay-rich siltstone and fine sandstone layers 1 to 5mm thick. The fine sandstone is commonly loading into the silt contorting remnant laminations within it. In some cases, the siltstone has faint ripple cross-lamination preserved.

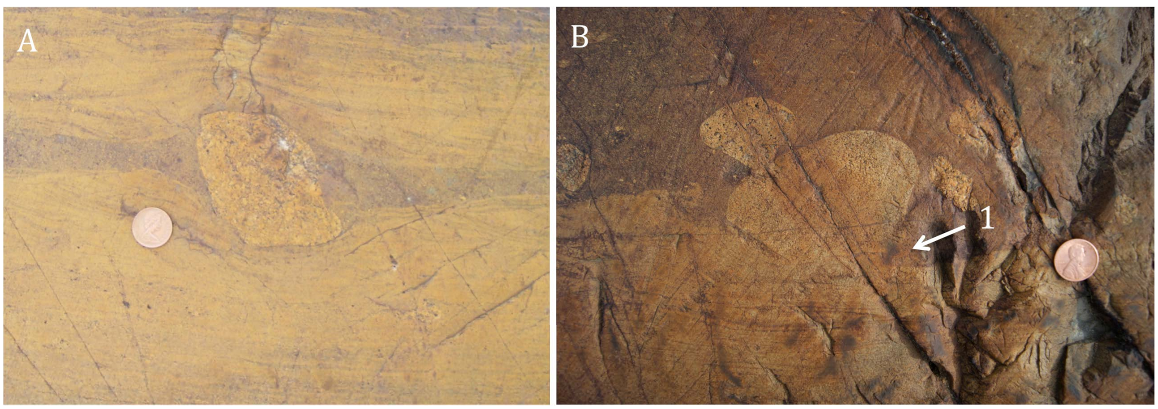


Figure 3.11 A) An outsized clast compressing laminations in the underlying sandstone layer. B) An erosive scour on the right side of the outsized clast is evidence for current activity (1).

3.3 Interlayered Siltstone and Fine-Grained Sandstone Lithofacies Association

In both the eastern and western sections logged in McGregor Bay there is a gradual contact with this LA from the uppermost diamictite layer. There is a progressive appearance of bedding as well as a gradual decrease in the number of outsized clasts. A stratigraphic column representing the typical interbedding of the LA is present in Figure 3.12A.

This LA is predominantly composed of interlayered silty-mudstone, mud-rich siltstone and very fine- to fine-grained sandstone layers (Fig. 3.12B). The silty-mudstone and mud-rich siltstone layers are generally 0.1 to 3cm thick whereas the sand layers are commonly thicker, with thicknesses averaging 5cm. The sand layers contained a number of different sedimentary structures including wave ripples, current ripples or thin, 1 to 3mm thick, parallel laminations. In the case of the ripples, mud flasers were commonly found within them (Fig. 3.12C). The sand also occured as lenses 0.4 to 8cm thick and 4 to 50cm in length, which, in places loaded into the muddy substrate. Also present are 1 to 4cm thick beds grading from fine-grained sand to silt to silty-mud. These were similar in structure to D-E turbidites as the basal portion of the layers often had parallel laminations. Occasional shale layers up to 35cm thick were also associated with the interlayered siltstone and sandstone.

The contacts between the sand layers and the underlying finer-grained layers were sharp but usually irregular, as the sand loaded the finer-grained sediments forming teardrop shapes or pseudo nodules with remnant laminations (Fig. 3.12D). In addition, the contacts can be marked by scalloped-shaped scours that were then filled with fine-grained sand that was often ripple reworked. These scours are indicative of an erosive contact.

In both the eastern and the western sections logged there is a gradual increase in thickness and frequency of sand layers up section over approximately 80 to 100m. The stratigraphic section in Figure 3.12A shows a fining upwards trend over the 2m that were logged in detail but this is not representative of the overall trend of the LA. The sand layers still average approximately 5 to 8cm but reach a maximum thickness

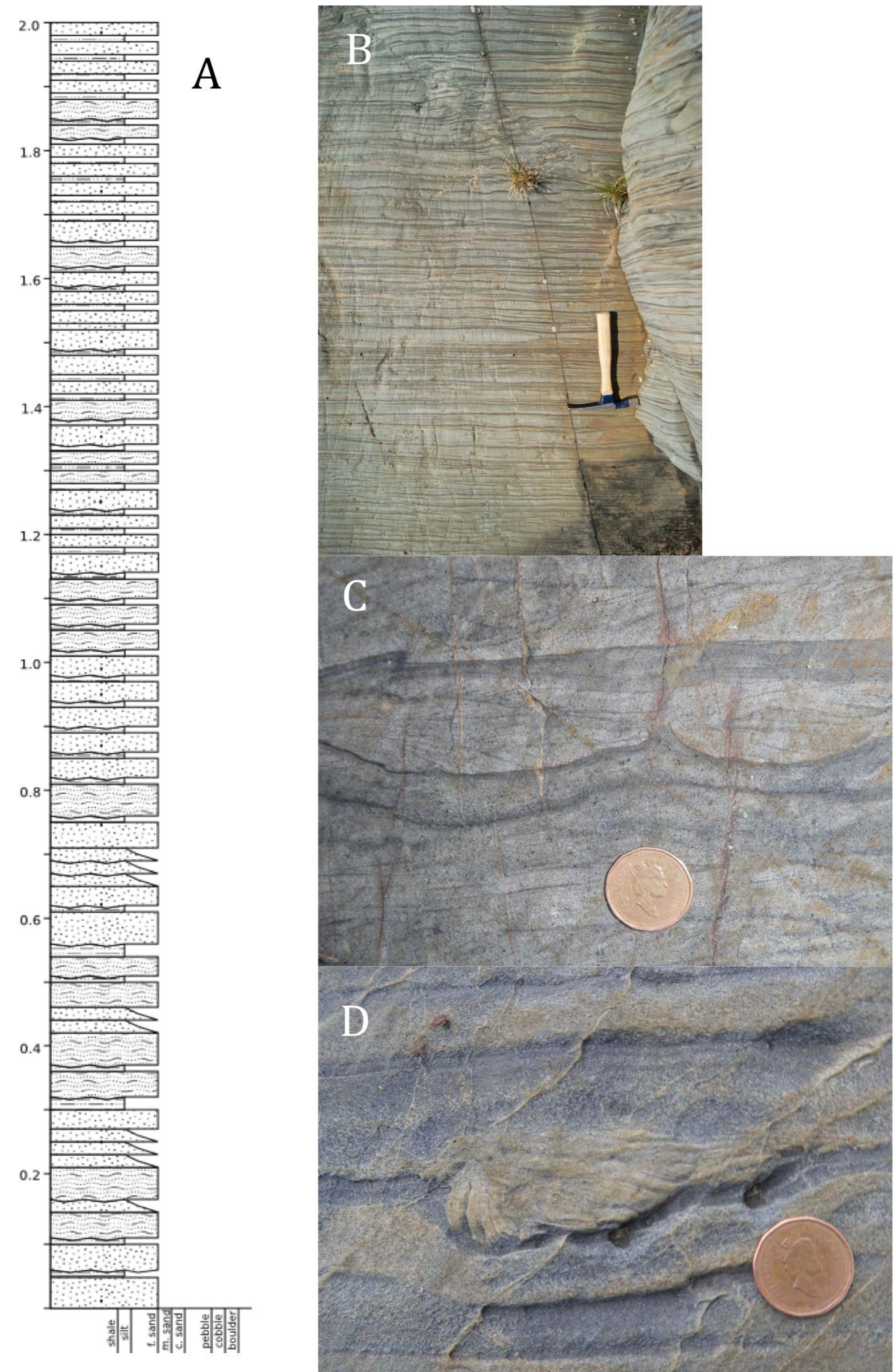


Figure 3.12 A) A stratigraphic column compiled in McGregor Bay of the Interlayered Siltstone and Fine-Grained Sandstone LA (scale in meters). B) Typical interlayered silty-mudstone, mud-rich siltstone and very fine- to fine-grained sandstone layers of the Interlayered Siltstone and Fine-Grained Sandstone LA. C) Mud flasers are present in the ripple laminated sandstone layers. D) A ripple lense loading into the underlying fine-grained sediments forming a teardrop shape (pseudo nodule).

of 40cm. The presence of current and wave ripples become more common as well. Wavy to lenticular bedding with some occurrences of flaser bedding are also present. The paleocurrent measured from the current ripples in both the eastern and western sections was trending east-northeast at approximately 065°. In the eastern section, the thickness of the graded beds also increases to a maximum of 38cm.

In the northern section, this LA makes two appearances. The first appearance was found stratigraphically above the diamictite LA just as in the eastern and western sections. The second appearance however, was located between the two occurrences of the fine- to coarse-grained sandstone LA.

3.4 Slump Lithofacies Association

The slump LA is composed of a highly contorted portion of the previously described interlayered siltstone and fine sandstone layers. In this case, these layers have extensive folds that lack cleavage and are chaotic and swirled meaning they are likely not the result of tectonic events. Stratigraphically above these folded layers, large rounded and contorted rip-ups of the interlayered siltstone and fine sandstone, 4 to 20cm thick and 5 to 60cm in length, are found within a clay-rich very fine- to fine-grained sandstone matrix (Fig 3.13A). Rip-ups of the diamictite as well as clay blocks approximately 12cm in diameter are also present. In addition to the rip-ups, rare outsized clasts of granite up to 70cm in diameter were found throughout the LA. In some areas, the layer is predominantly composed of a contorted fine sandstone and slightly more clay-rich fine sandstone (Fig 3.13B).

In the western section, this LA was found initially within the Diamictite LA but it should be noted there is a fold in the formation in this area. The second occurrence was found at the top of the Interlayered Siltstone and Fine Sandstone LA and was approximately 17m thick. In the eastern section, the slump LA was also found stratigraphically overlying the Interlayered Siltstone and Sandstone LA and was roughly 134m thick. In the northern section, there was nothing visible that resembled the Slump LA present in the other two sections.

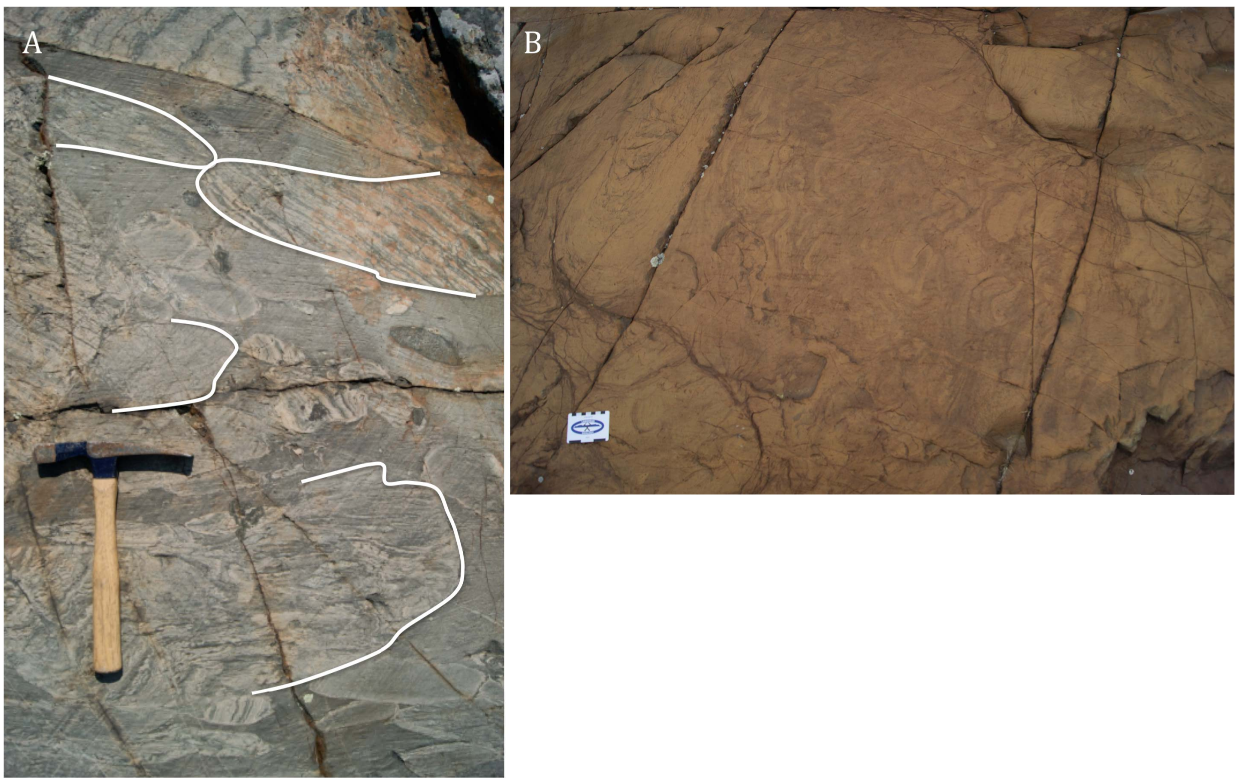


Figure 3.13 A) Large, rounded and contorted rip-ups of the Interlayered Siltstone and Fine-Grained Sandstone LA in a clay-rich sandstone matrix compose the Slump LA. B) The chaotically bedded sandstone of the Slump LA.

3.5 Heterogeneous Sandstone Lithofacies Association

In the eastern and western sections, there is a relatively sharp contact between this LA and the underlying Slump LA. In the northern section, which lacks a Slump LA, the contacts seem to be gradual as there is a progressive increase in the number and thickness of sandstone layers stratigraphically upsection through the Interlayered Siltstone and Fine Sandstone LA. A detailed stratigraphic column is shown in Figure 3.14A.

This LA is composed predominantly of fine- to coarse-grained sandstone layers, interbedded with thin shale layers, that often contain a variety of sedimentary structures within one layer (Fig. 3.14B). These layers are approximately 40cm thick in the lower portion of the LA and generally tend to thicken up-section to an average of 1.0 to 3.0m thick. In addition, the layers are commonly topped by a 2 to 6cm current or wave ripple reworked section rich in mud flasers and drapes (Fig. 3.14C).

Parallel laminated fine- to coarse-grained sandstone layers ranged from 0.19 to 9m and averaged 2.1m. They comprised either an entire layer or were found solely in the basal portion of layers. Rare 1mm thick clay layers are present interbedded with the parallel laminated sandstone layers.

Medium- to fine-grained sandstone layers with low-angle planar cross-stratification dipping at approximately 8° to 10° are found throughout this LA and seem to be more abundant upsection (Fig. 3.15A). These layers range in thickness from 0.13 to 9.0m, averaging 1.8m, and are sometimes observed lensing out. In the east, occasionally trough cross-stratified sandstone is observed cutting into the tops of the planar cross-stratified layers. The paleocurrent measurements obtained from

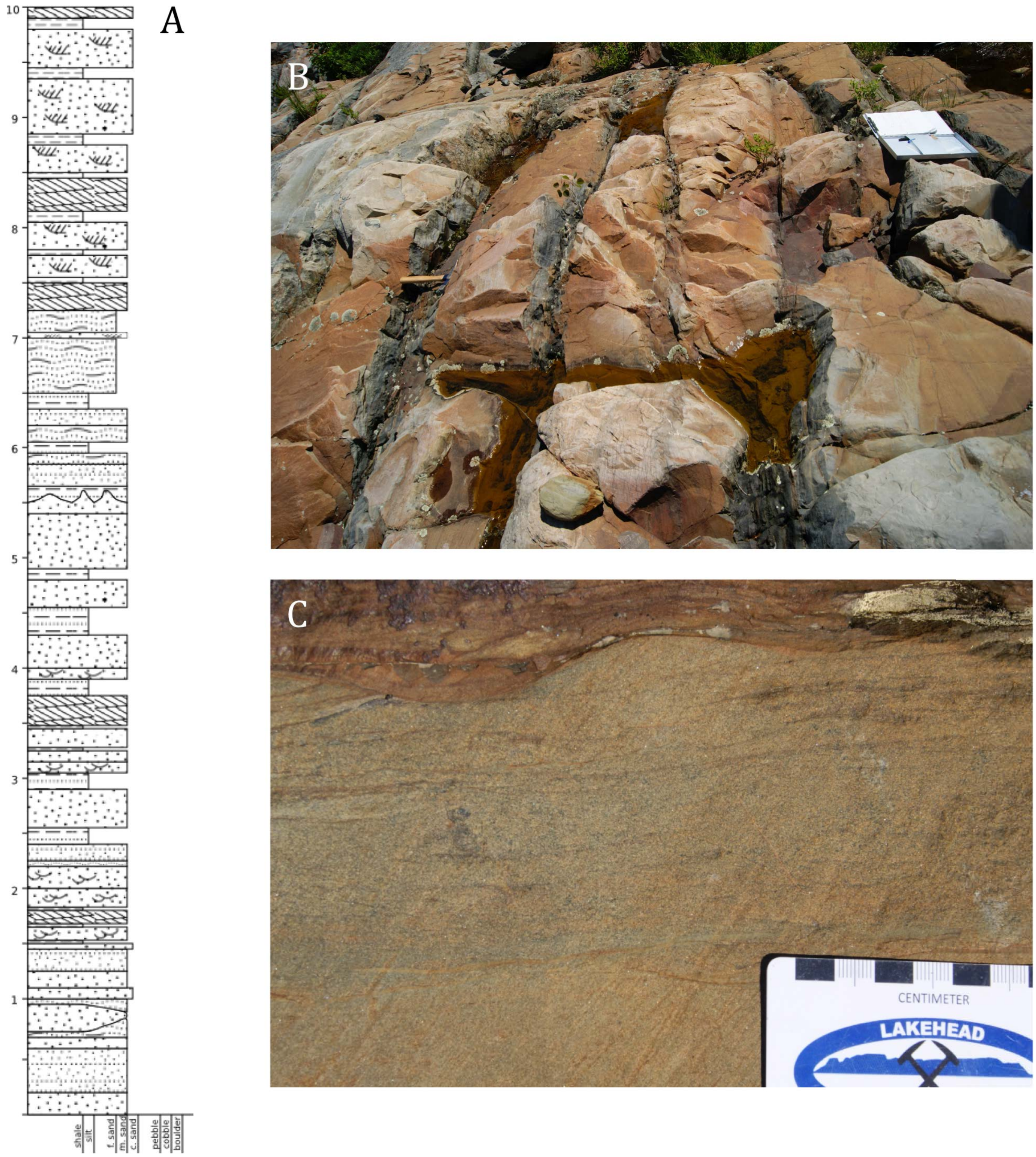


Figure 3.14 A) A detailed stratigraphic column of the Heterogeneous Sandstone LA (scale in meters). B) Typical sandstone layers with interbedded shale layers of the Heterogeneous Sandstone LA (note the field book in the top right corner that is 35cm long for scale). C) Sandstone layers commonly topped by current- or wave-ripple reworking.

these cross-stratified units in addition to paleocurrent measurements taken from some of the ripple reworked tops of layers are shown in a rose diagram in Figure 3.16A. The rose diagram shows a strong trend for the paleocurrents to the northeast with a minor trend to the southeast. This indicates the predominant current direction would have been in the northeast to southwest direction at this time. In the north, rare lenses 3cm thick and 20cm in length, composed of coarse-grained sand and mud rip-ups, are found within these layers. There is a second succession of this LA in the northern section, which is separated from the initial occurrence by approximately 65m of the Interlayered Siltstone and Fine-Grained Sandstone LA. This second section is composed predominantly of medium-grained sand layers containing large scale low-angle planar cross-stratification. The paleocurrent data for these units is compiled in a rose diagram in Figure 3.16B showing trends to the northeast and southwest with a minor trend to the northwest.

The low-angle trough cross-laminated sandstone layers are commonly associated with linguoid or lunate ripple laminations in the northern section predominantly near the top of the first succession of the LA as well as in the second (Fig. 3.15B). These layers, or horizons, range from 0.15 to 1.0m and contain abundant mm thick clay drapes and flasers throughout the laminations. Hummocky cross-stratified layers were documented in the sandstone layers of the eastern section ranging from 12 to 20cm thick and containing abundant mud flasers and drapes throughout the stratification (Fig. 3.15C).

Another feature observed in the sandstone layers is grading. In the western section, small layers, approximately 5cm thick, grade from fine-grained sand to mud are observed in one grouping of five layers. In the eastern section however, a 9.5m section that resembles B-C-E turbidites was documented. The basal portion of these layers are composed of fine- to medium-grained parallel laminated sandstone passing into ripple cross-stratified fine sandstone with some ball and pillow structures followed by mud caps. The graded layers range from 18 to 30cm thick with the mud portion measuring 6 to 11cm. Sand from the overlying layers often loads into the mud portion making the contacts irregular. This section of turbidites was documented

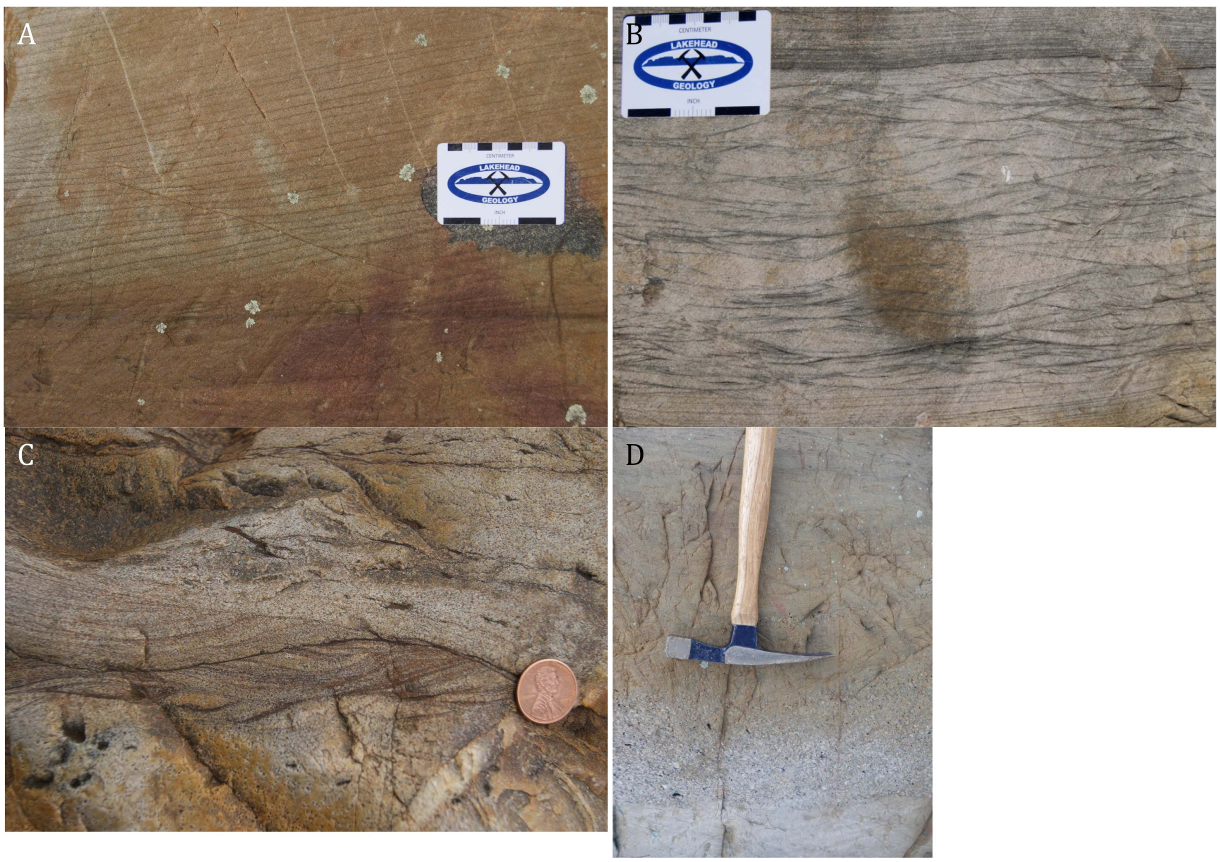


Figure 3.15 A) Planar cross-stratified sandstone layers common to this LA. B) An example of the linguoid or lunate ripples. C) Low-angle truncations of hummocky cross-stratification. D) An example of a sandstone layer graded from very coarse- to medium-grained sand.

stratigraphically overlying a section in the LA that had abundant hummocky cross-stratification. In the northern section, layers graded from very coarse- to medium-grained sand are present (Fig. 3.15D).

The ball and pillow structures observed in the graded layers are also common elsewhere in the sandstone layers of the LA. Ball and pillows of fine- to medium-grained sand 5 to 7cm thick and 12 to 15cm in length were often found in a matrix that was of similar composition or slightly more mud-rich (Fig. 3.17A). These balls and pillows had remnant laminations preserved within them and generally comprised a layer between 12 to 30cm thick.

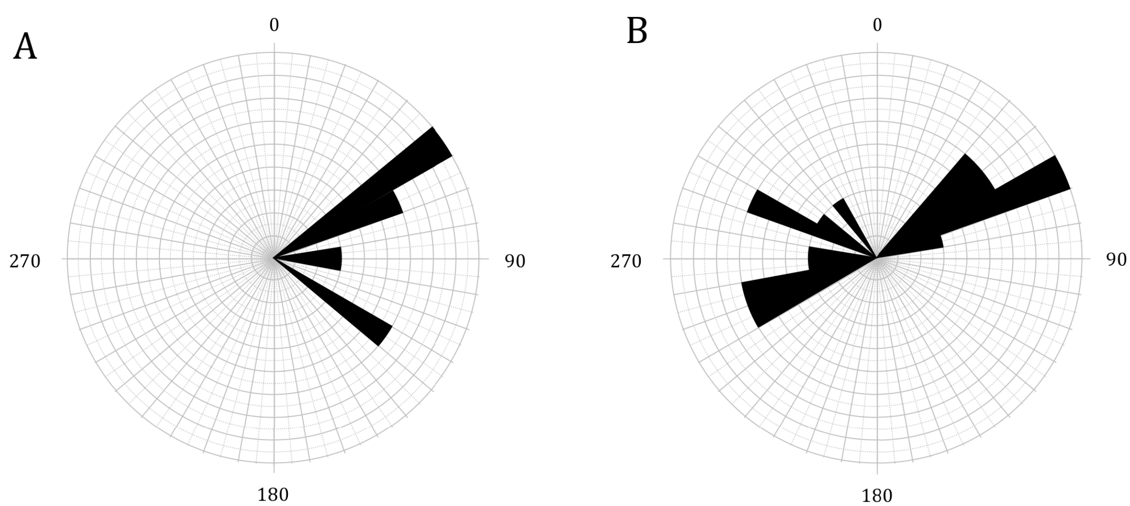


Figure 3.16 A) A rose diagram compiling all of the 20 paleocurrent measurements taken from the first succession of the Heterogeneous Sandstone LA provides a strong trend for paleocurrents to the northeast with a minor trend southeast. B) A rose diagram compiling all of the 18 paleocurrent measurements taken from the second succession of the Heterogeneous Sandstone LA provides strong trends for paleocurrents to the northeast and southwest a minor trend to the northwest.

The sandstone layers are commonly interbedded with various types of heterolithic bedding, the most common being a lenticular-like mud layer with fine- to medium-grained sandstone lenses 0.5 to 10cm thick and 5 to 195cm long (Fig. 3.17B).

The sand lenses appeared as though they were layers with frequent current ripple cross-lamination, which broke apart as they loaded into the mud. These lenticular layers range from 7 to 26cm thick and average 13cm. In the eastern section, these layers are interlayered with the sandstone for approximately 18m. Lenticular layers in the northern section contain rare outsized clasts of granite from small pebbles to small cobbles up to a maximum of 7cm in diameter. Layers of wavy interbedded siltstone to fine-grained sandstone and mudstone, 0.05 to 7.0m thick and averaging 1.02m, are also commonly found associated with the sandstone layers (Fig 3.17C). The silt to fine-grained sandstone layers range from 0.8 to 2.5cm thick while the mudstone layers are between 0.1 to 1cm thick. In some cases, sections of the sandstone layers are flaser bedded with abundant wave ripples and a large number of clay drapes and flasers along the forsets.

In some cases, massive shale layers, 0.2 to 1.0m thick, are found interlayered with the sandstone. In the first succession of the LA in the northern section, three silty-mud layers, measuring 18cm, 18cm and 51cm thick respectively, were documented containing granitic outsized clasts from granule- to cobble-sized (Fig. 3.17D). These diamictite-like layers have sharp contacts with the adjacent sandstone and are thought to be a second small succession of the Diamictite LA. In one case, a contorted sand layer with remnant laminations is contained within the silty-mud layer.

In the first succession of the LA logged in the northern section, the massive fine-grained to coarse-grained sandstone layers have a gradual increase in the number of coarser grain-sizes upsection. Lenses, 10 to 25cm thick and 1 to 4.5m long, of very coarse-grained sand, granules and small pebbles become more common upsection as

Figure 3.17 A) Ball and pillow structures commonly with remnant laminations preserved within them. B) Lenticular-like bedding with lenses of fine- to medium-grained sandstone in a mudstone matrix. C) Layers of wavy bedded siltstone to fine-grained sandstone and mudstone. D) Diamictite-like layers interbedded with the sandstone of the Heterogeneous Sandstone LA in the northern study area.

well. In addition, there is one 15cm thick very coarse-grained to granule-sized sand layer with small pebbles and cobbles. This coarse layer also contains rip-ups of medium sand and mud-rich silt that average 4cm in diameter. Lastly, an 18m thick section of sand is present at the top of the first occurrence of this LA in the northern area, containing abundant outsized granitic clasts up to cobble-sized. These granite clasts are randomly distributed throughout the sand and gradually decrease upsection over 4m with one 10cm thick matrix-supported, clast-rich horizon present 3.5m from the base. The medium- to coarse-grained massive sandstone layers in the eastern and western sections did not contain these outsized granitic clasts.

3.6 Quartz-Rich Sandstone Lithofacies Association

The transition from the Gowganda Formation to the Lorraine is a gradual one. In the eastern section, the initial 60m of outcrop is composed of alternating layers of sandstone and shale similar to the upper portion of the Heterogeneous Sandstone LA. The sandstone layers are predominantly fine-grained and average 1m thick while the shale layers range from 4 to 10cm thick. The sandstone has low-angle planar cross-stratifications, current ripples and some minimal horizons of flaser bedding. In addition, the outcrop in the eastern section had abundant herringbone cross-stratification (Fig. 3.18A). Paleocurrent measurements taken from the herringbone cross-stratification were 45° and 225° as well as 70°, 80° and 280°. Paleocurrent measurements for the LA are compiled in a rose diagram in Figure 3.18B. The data shows strong trends to the northeast and southwest for the paleocurrent directions. Following approximately 150m of cover, the Lorraine Formation transitions into quartz-rich sandstone. The outcrop is composed of quartz-rich sandstone in layers 10 to 90cm thick that averaged 45cm (Fig. 3.18C). Graded beds were visible from coarse- to medium-grained sandstone.

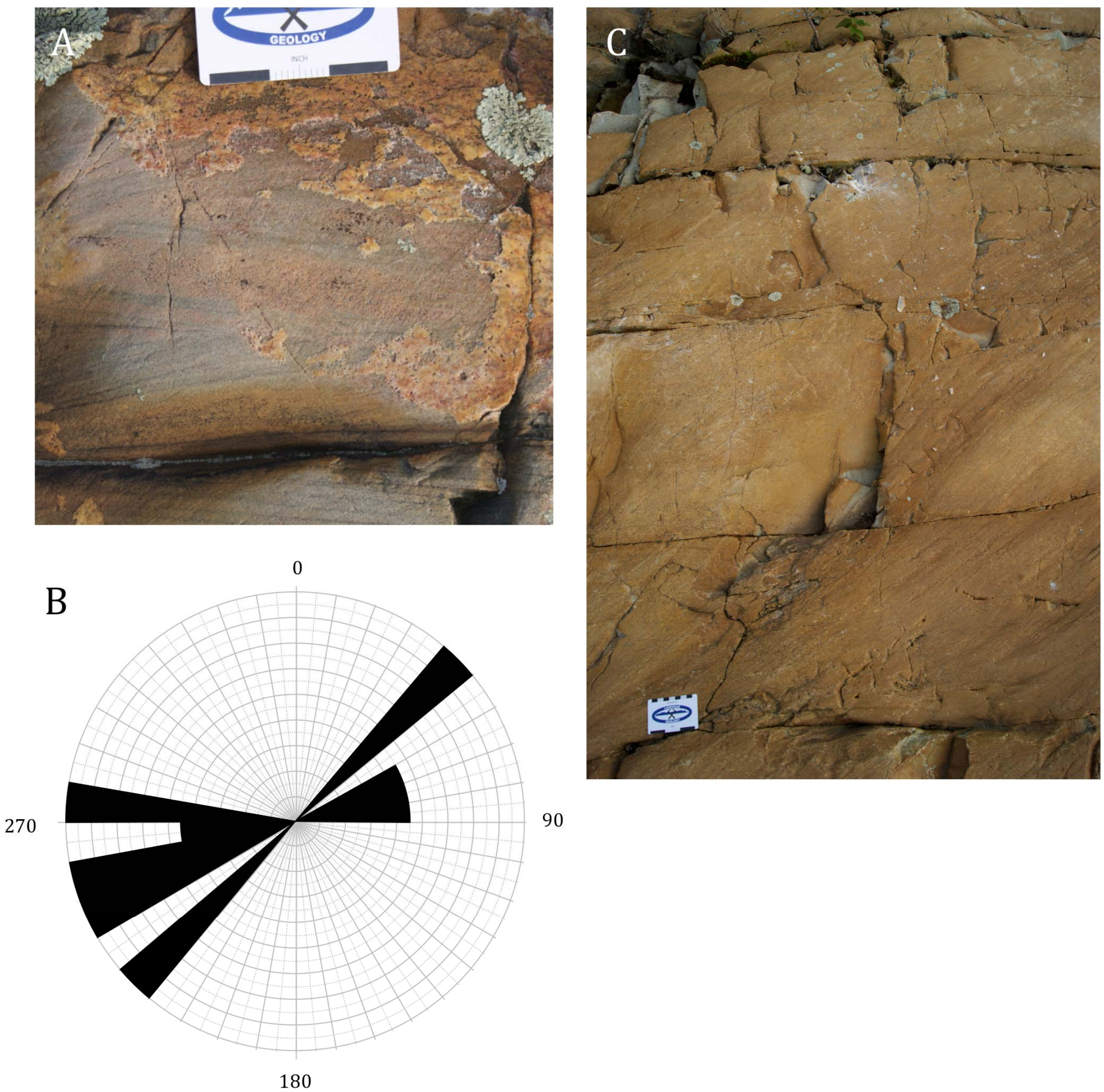


Figure 3.18 A) Herringbone cross-stratification with the characteristic 180° alternating directions of planar cross-stratification. B) A rose diagram compiling all 14 of the paleocurrent measurements taken from the Quartz-Rich Sandstone LA provides a strong trend for paleocurrents to the northeast and southwest. C) The quartz-rich sandstone layers indicative of the basal portion of the Lorraine Formation.

4. ELLIOT LAKE STUDY AREA LITHOFACIES ASSOCIATIONS

A map of the Espanola study area with the locations where outcrops were logged to compile data is shown in Figure 4.1. Drill core data provides the best overall stratigraphic column of the Gowganda Formation in the Elliot Lake area. The core used was from holes 150-1 (Zone 17 0377100E 5146200N) and 150-4 (Zone 17 0369800E 5147700N) that were drilled in the late 1960s by Kerr-McGee Corp. and were examined at the Ontario Geological Survey storage facility in Sault Ste. Marie, Ontario. An overall general stratigraphic column of the area was compiled from this data (Fig. 4.2).

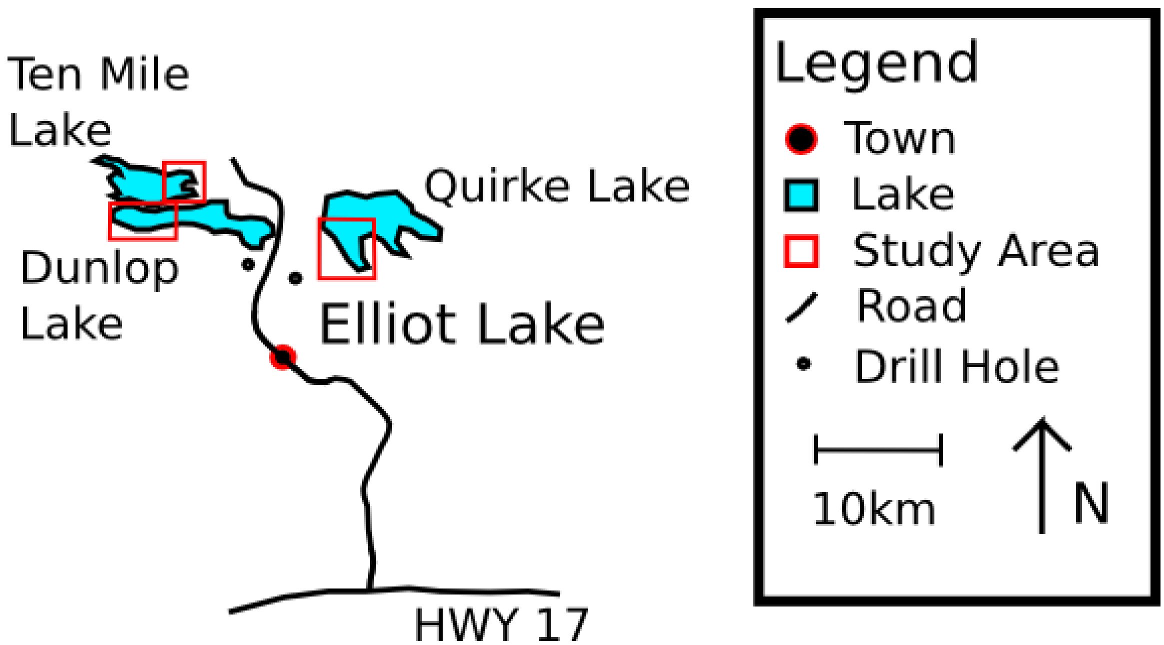


Figure 4. 1. A map of the Elliot Lake study area showing the locations where outcrops were logged to compile stratigraphic columns of the area. The drill holes are located to the southeast of Dunlop Lake and the southwest of Quirke Lake (black circles).

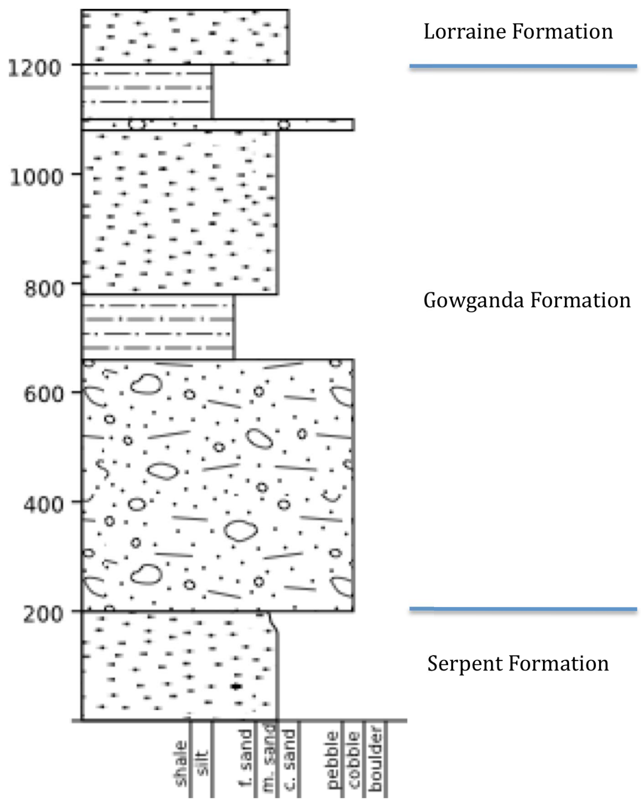


Figure 4.2 A very general overall stratigraphic column of the Elliot Lake area compiled from drill core data (scale in meters).

4.1 Planar Cross-Stratified Sandstone Lithofacies Association

The uppermost portion of the Serpent Formation in the Elliot Lake area is composed of predominantly medium- to coarse-grained, quartz-rich sandstone with some occasional very coarse- to granule-sized grains dispersed throughout. These layers ranged from 10cm to a maxiumum of 8m thick and averaged 2 to 4m.

In outcrop, faint parallel lamination and low-angle planar cross-stratification are often present, otherwise the sandstone layers are massive. Wave ripples commonly dominate the upper 7 to 12cm of most of these sandstone layers. Up section, near the base of the diamictite, mud is interlayered with the sandstone. The mud layers are generally 0.1 to 4cm thick and have sharp contacts with the sandstone. Thin layers of medium- to coarse-grained sand, 1 to 7mm thick, as well as injection features, were sometimes observed within the mud layers. Data collected from drill core provided a better overview of this LA than the outcrops themselves especially for compiling a more detailed stratigraphic column (Fig. 4.3).

Within the drill core, medium-grained sandstone layers dominate the Planar Cross-Stratified Sandstone LA. The most prevalent of which are massively bedded sandstone layers ranging from 29 to 490cm in thickness, but averaging 172cm. Stratigraphically up section, these layers become finer-grained and more mud-rich. Small rounded or elongated spots of quartz- and feldspar-rich sand, 1 to 7mm thick, and up to 4cm long also appear within the sand layers (Fig. 4.4A). Similar sized spots of grey mud-rich sediment are present within quartz-rich medium-grained sand layers. These spots increase in frequency up section within the LA and are either found dispersed throughout an entire sandstone layer or confined to horizons 10-60cm thick. In some cases, medium-grained, quartz-rich sand layers or small mounds, 0.2 to 1.2cm thick, are interlayered in the mud-rich, fine-grained sandstone (Fig. 4.4B).

Parallel laminations are also visible within some of the sandstone layers. These laminations are usually accentuated by thin mud layers approximately 1mm thick. The laminations are confined to layers 10 to 540cm thick, but averaging 166cm. In some cases the laminations are in specific horizons, most commonly in the basal or uppermost 10cm of a layer and rarely throughout the central portion. Layers 4 to 6cm

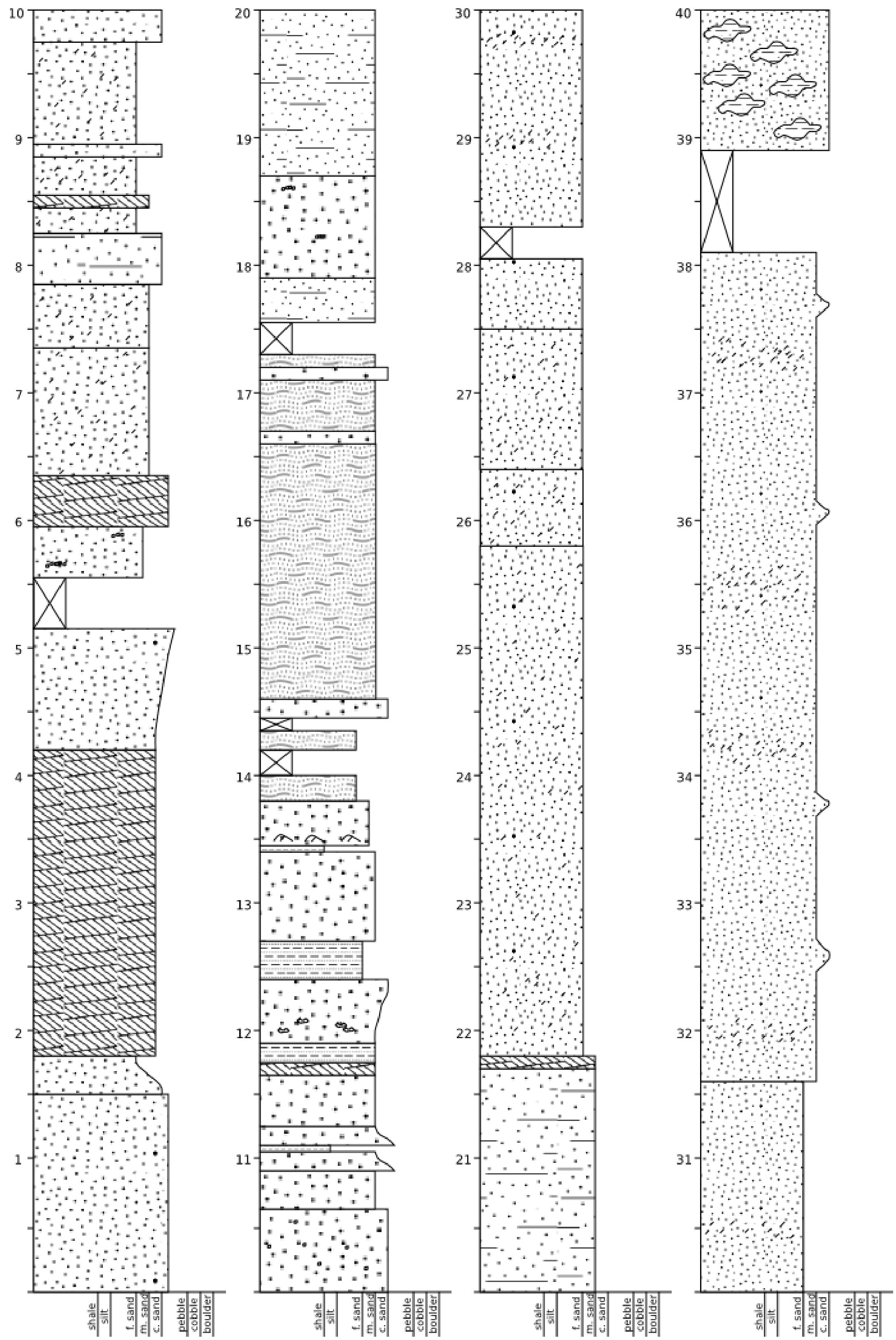


Figure 4.3 A stratigraphic column of the Planar Cross-Stratified Sandstone LA, comprising the uppermost portion of the Serpent Formation, in the Elliot Lake study area (scale in meters).

thick, composed of 1cm deep scours, were documented within the parallel laminations (Fig. 4.4C).

Layers of cross-laminated, quartz-rich sand with thin, 1mm thick, mud drapes measure between 10 and 240cm thick and average 100cm. The cross-stratification generally dips at 25 to 30°. In some cases, the cross-laminations are truncated by an erosive upper surface, which is accentuated by a thicker mud layer approximately 2 to 3mm thick (Fig. 4.4D).

Graded layers are also present interlayered with the predominantly medium-grained sandstone of this LA. These layers grade from coarse-grained sand to fine-grained, clay-rich sand. The graded layers measure 15 to 30cm in thickness, and average 20cm.

Just as in outcrop, the drill core commonly shows wave ripples, draped by thin mud layers, which are present in the upper portion of the medium-grained sandstone layers within this LA. In addition, wavy bedded layers 10 to 42cm thick and averaging 23cm are present within the LA. These layers are composed of fine- to medium-grained sandstone with 1 to 2 mm thick clay drapes and flasers (Fig. 4.5A).

Although medium-grained sandstone dominates this LA, interlayered silty-mudstone, fine-grained sandstone and coarse-grained sandstone are common. The sandstone layers are between 0.2 and 10cm thick whereas the mud layers are 0.1 to 4cm. Injection features are commonly associated with these layers and in one outcrop the upper surface was visible showing the angular chunks of silty-mud separated by the fine- to medium-grained sand organized in a puzzle-piece fashion (Fig. 4.5B).

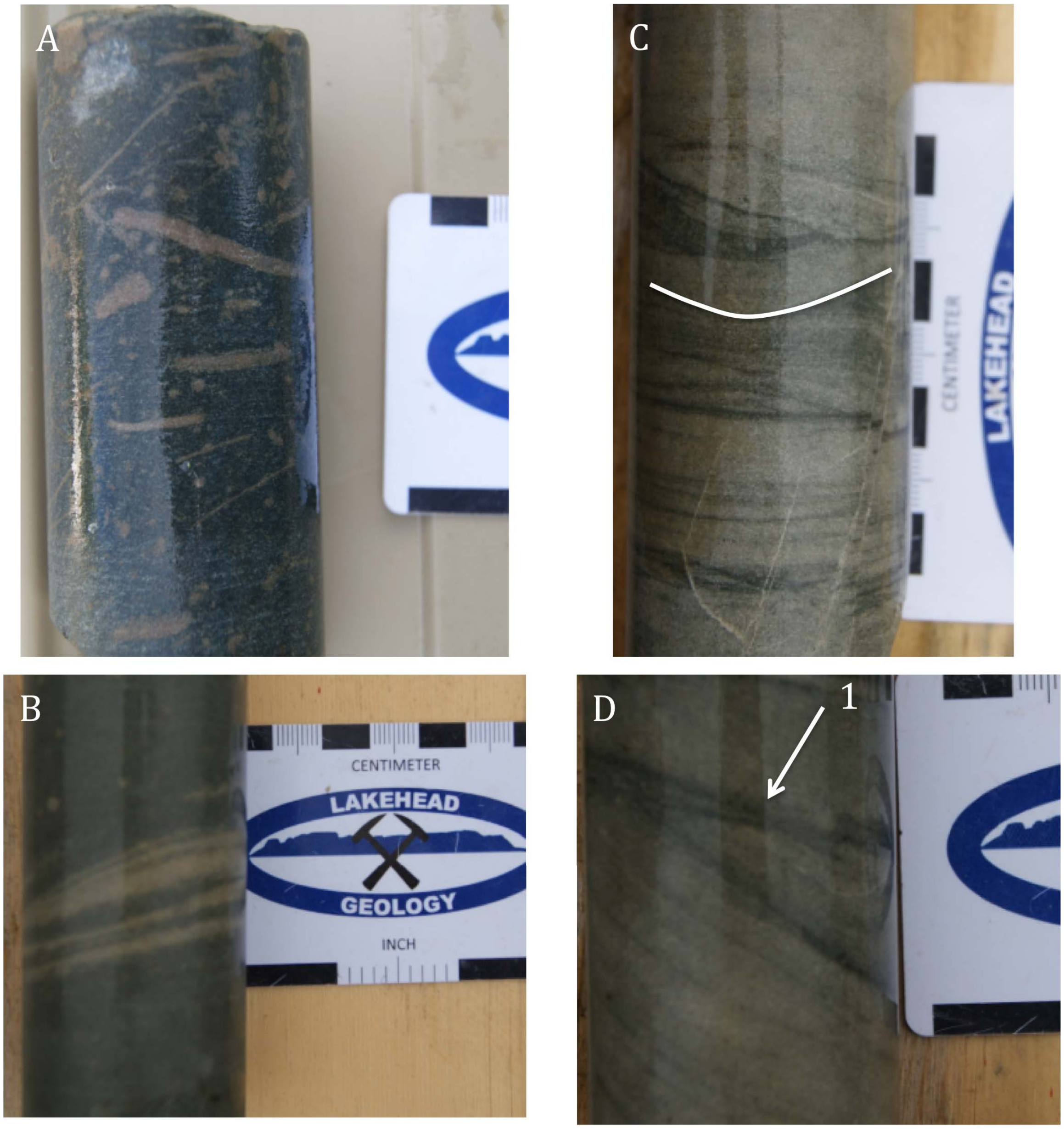


Figure 4.4 A) Small, rounded or elongated spots of quartz- and feldspar-rich sand within a more mud-rich sandstone matrix. B) A small mound of quartz-rich sand interlayered with mud-rich fine-grained sandstone. C) Scours visible cutting down into underlying parallel laminations. D) Erosive upper surface accentuated by a thin mud layer that is truncating cross-laminations (1).

Throughout the upper portion of the LA, mud rip-ups 1 to 4cm long and 0.5 to 0.7cm thick are commonly found within the sandstone layers. Rip-ups are usually confined to the basal and uppermost portions of the sandstone layers. Some isolated continuous layers of mud, 1 to 3mm thick, are also present. In addition to the rip-ups and mud layers, 30 to 40cm thick layers of coarse- to very coarse-grained sandstone also become more frequent upsection. These layers also contain mud rip-ups and are associated with the mud-rich fine-grained sandstone found in the upper portion of the succession at approximately the same level as the horizons of small spots of sand and clay. The contacts between these layers and the adjacent muddy-sand layers are gradational. In two locations, there are two to four of these coarser layers found within one larger muddy-sandstone layer. The upper limit of this LA is gradational into the Diamictite LA with a gradual decrease of the coarse- to very coarse-grained sand into the muddy-siltstone matrix of the lowermost diamictite layer.

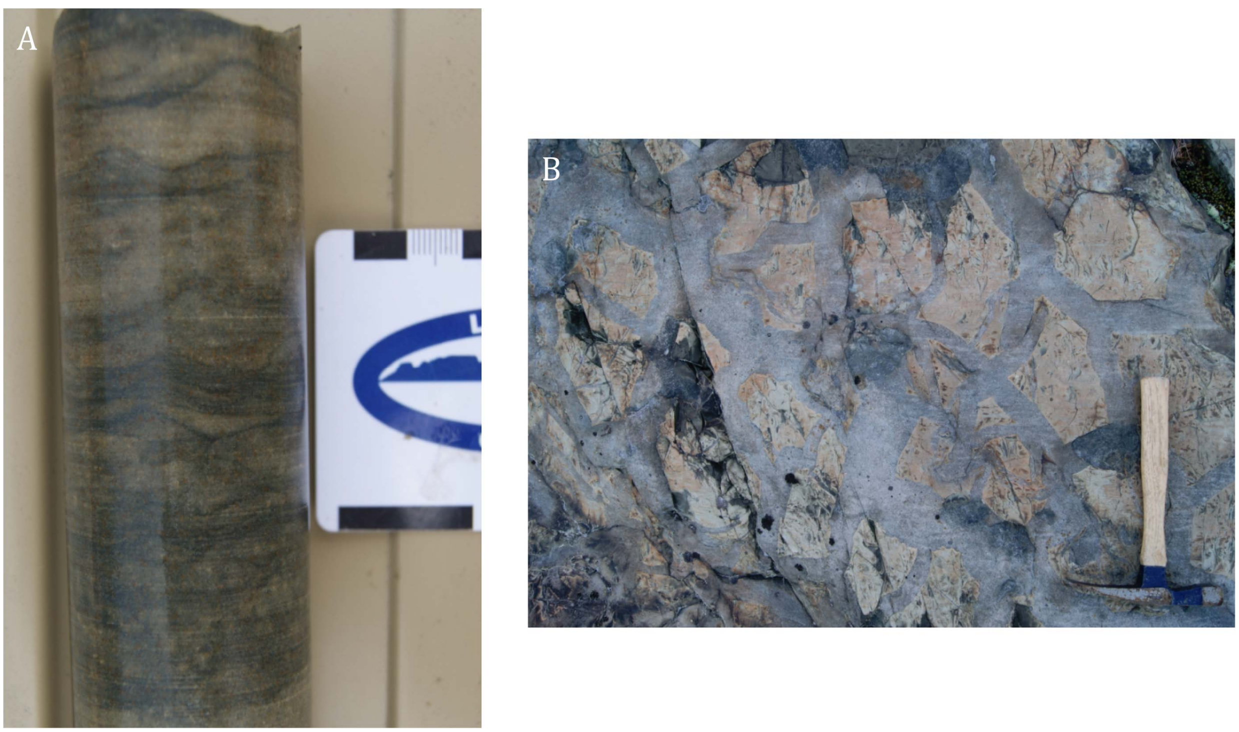


Figure 4.5 A) Wavy bedding in drill core composed of fine- to medium-grained sandstone with abundant clay drapes and flasers. B) An outcrop of angular chunks of silty-mudstone separated by fine- to medium-grained sandstone.

4.2 Diamictite Lithofacies Association

A stratigraphic column compiled from drill core data shows the interlayering of diamictite, conglomerate and sandstone layers within the Diamictite LA (Fig. 4.6A). Just as in the Espanola area, the Diamictite LA is composed predominantly of diamictite layers with a muddy-siltstone matrix that has fine- to coarse-grained sand dispersed throughout. Outsized clasts within these layers are granule- to boulder-sized, the largest reaching 155cm in diameter. These clasts are subangular to subrounded and are predominantly of granitic composition, although on Quirke Lake rare pebble-sized clasts of jasper were observed (Fig. 4.6B). From the drill core that was analyzed, the basal approximately 42m of the Diamictite LA appears to contain a high percentage of white-coloured granitic clasts. Following the initial 42m, there is a gradual increase in the percentage of pinkish-red granitic clasts.

Layers and lenses of medium- to coarse-grained, pink, feldspar-rich sandstone approximately 1 to 300cm thick and 4 to 650cm in length are commonly interbedded with the massive diamictite layers (Fig. 4.6C and 4.7A). These sand layers are predominantly well-sorted but also have common patches of coarse- to very coarse-grained sand within them, as well as some rare granule to cobble outsized clasts of granite. The outsized clasts are not as common in the sand layers as they are in the interlayered diamictite layers. The contacts between the sand and the diamictite layers can be sharp, with abundant loading structures, or gradual (Fig. 4.7A). Where sharp contacts occur, larger outsized clasts at the top of the diamictite layers can protrude up into the sandstone layer. Upsection, these sandstone layers have rare parallel laminations and wave ripples with clay drapes (Fig. 4.7B). In addition, rip-ups

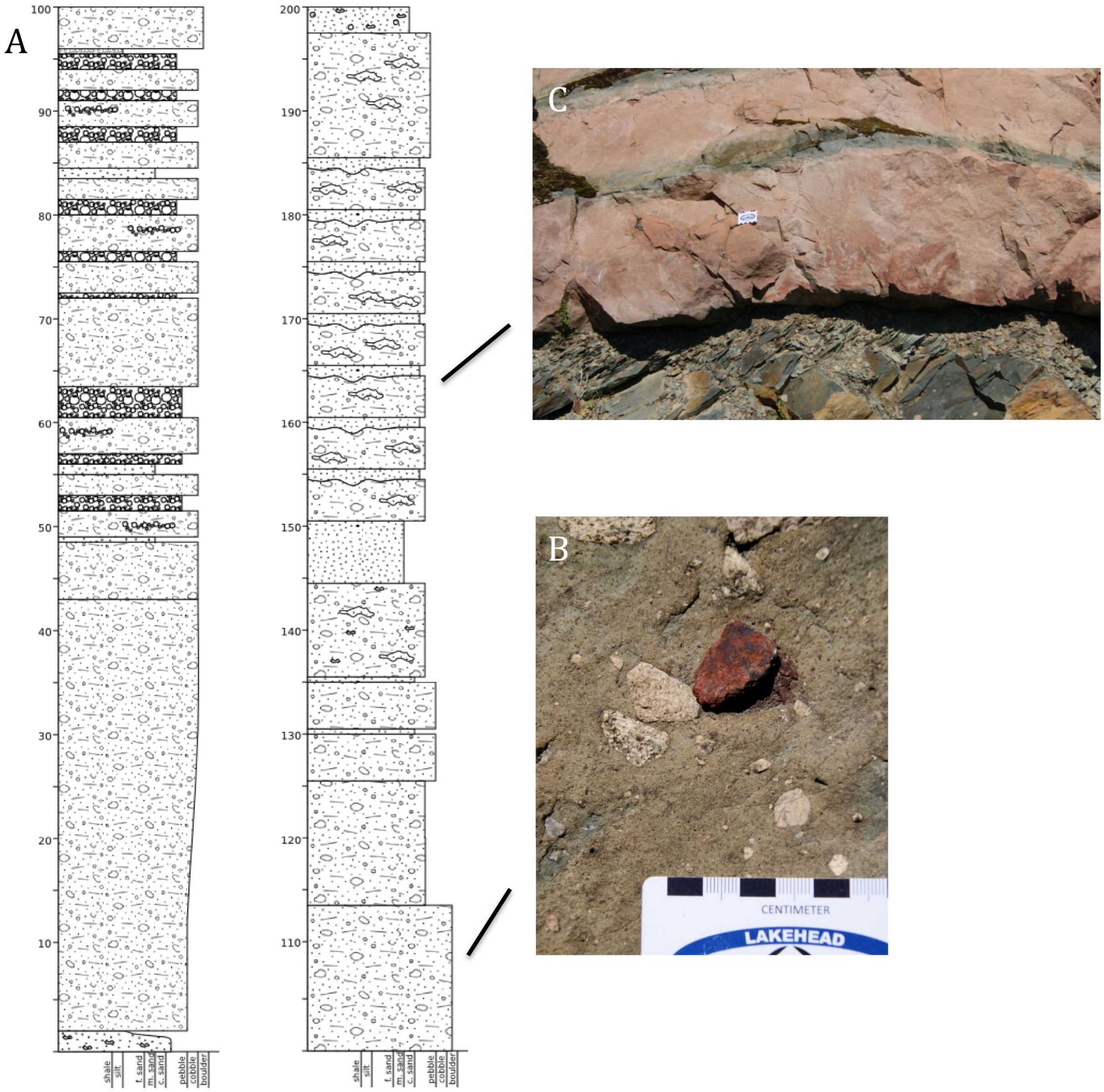


Figure 4.6 A) A stratigraphic column of the Diamictite LA compiled from drill core (scale in meters). B) Subangular to subrounded outsized clasts randomly dispersed throughout the diamictite matrix. Clasts are mainly granitic but rare clasts of jasper, such as this one, were also present. C) Well-sorted sand layers and lenses that are interbedded with the diamictite.

of the silty-mud matrix of the diamictite layers are present within the sandstone layers. The rip-ups are commonly confined to the basal 30 to 40cm and the uppermost 5cm of the sandstone layers. In outcrop along Highway 108, north of the town of Elliot Lake, an outcrop of interfingering layers of diamicite and large sandstone lenses is visible. In this outcrop, the sandstone also occurs as very angular blocks (Fig. 4.7C) or sometimes as irregular shaped patches or lenses that are concave-up like loading structures (Fig. 4.7D), within the diamictite layers.

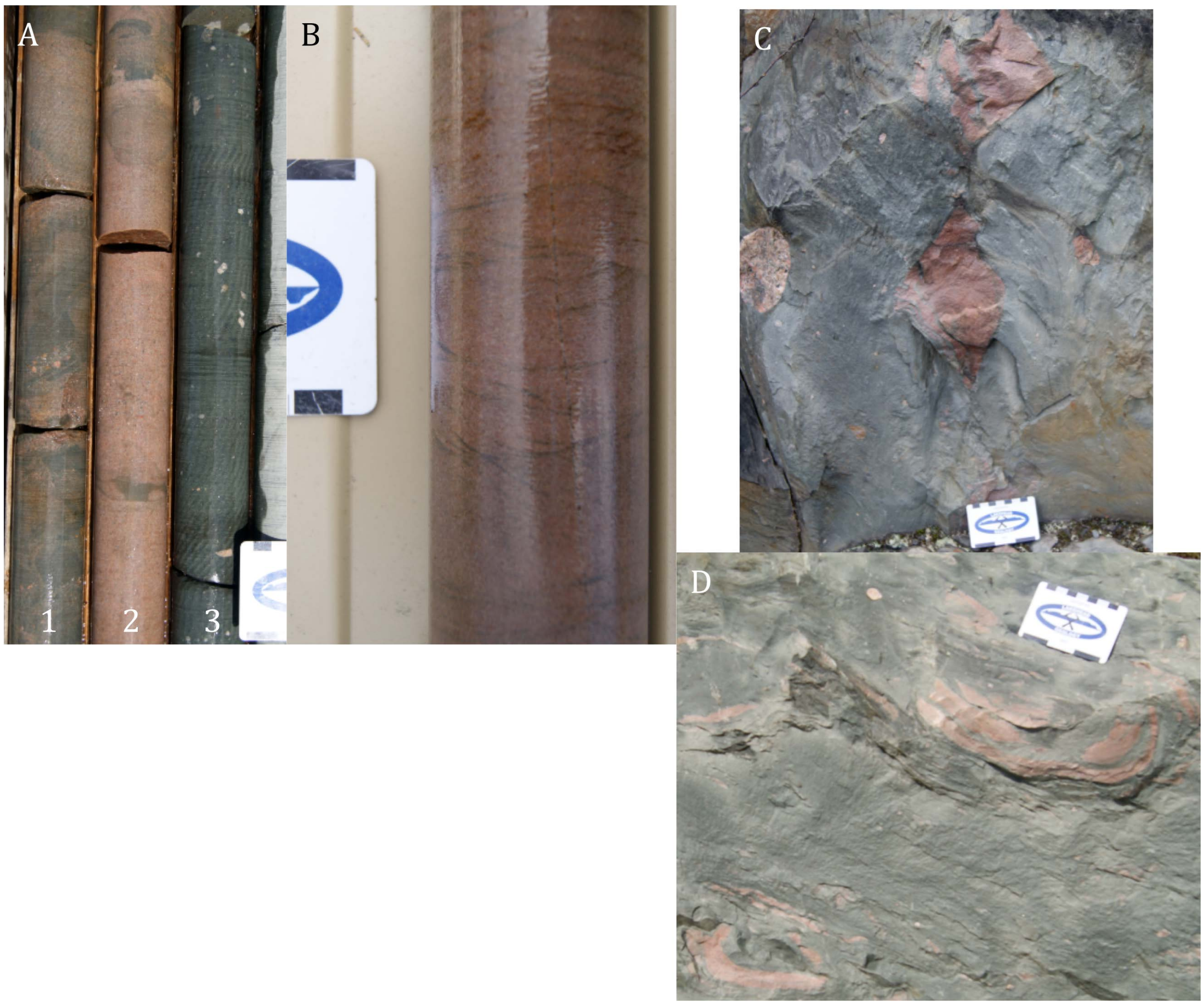


Figure 4.7 A) A comparison of drill core in the diamictite lithofacies. A gradual contact is shown in 1 between diamictite matrix and the sandstone layer in 2. The mud-rich siltstone matrix of the diamictite is shown in 3. B) Wave ripples with clay drapes in one of the interlayered sandstone layers of the Diamictite LA. C) Sandstone as angular chunks or D) as irregular shaped patches or lenses that are concave-up like loading structures within the diamictite matrix.

Clast-supported conglomeratic layers of subrounded to rounded clasts are also common within the Diamictite LA. These layers measure 2 to 300cm thick, but average 34cm thick. The clast sizes range from very coarse-grained sand to cobble-sized and are commonly, although not exclusively, arranged in graded beds (Fig. 4.8A). Very rare boulder-sized clasts are present. The basal 5 to 10cm of these clast-rich layers are often reverse graded (Fig. 4.8B) as was also observed by Miall (1985). Mud rip-ups are also present within these layers and average approximately 2 to 4cm thick and 4 to

Figure 4.8 A) Drill core of a conglomerate layer showing normal grading. B) Clast-supported conglomerate layer showing reverse grading in the basal portion of the layer. C) Stringers or small lag deposits are common in the diamictite layers and are often present just above or below the conglomerate layers. D) Highly contorted coarse-grained sandstone that shows possible evidence of lateral movement of trough cross-stratified sandstone smeared through the diamictite matrix.

7cm long. The conglomeratic layers are predominately interlayered with the diamictite layers but in some cases also with the medium-grained sandstone. Stringers, one clast thick, or small lag deposits are often present within the diamictite layers stratigraphically just above or just below the conglomeratic layers (Fig. 4.8C). The lowermost portion of the Diamictite LA visible on Quirke Lake commonly contains these clast-supported conglomeratic layers, stringers and small lag deposits. These are interlayered with clast-poor layers of matrix. The clast-poor layers appeared to have parallel laminations.

In one outcrop on Highway 108, north of Espanola, highly contorted remnant coarse-grained sandstone layers 1 to 4.7cm thick are visible. These contorted layers contain possible evidence of lateral movement as they appear to be possible trough cross-stratification that has been smeared within the diamictite matrix. Outsized clasts are still present throughout this layer and are more angular to subangular in shape (Fig. 4.8D).

4.3 Interlayered Siltstone and Fine-Grained Sandstone Lithofacies Association

There are minimal outcrops of the Interlayered Siltstone and Fine-Grained Sandstone LA in the Elliot Lake area. Data from a number of small outcrops were compiled to make an overall stratigraphic column of the LA (Fig. 4.9A).

Alternating layers of clay-rich siltstone, 0.1 to 5cm thick, and clay-poor layers of siltstone to fine-grained sandstone, 0.1 to 1cm thick dominate this LA. These layers have sharp contacts that are usually parallel to bedding but do take on a wavy appearance in places (Fig. 4.9B). Stratigraphically higher up in the LA, 2 to 5cm thick, clay-poor siltstone to fine-grained sandstone layers are present approximately every 10cm. Thin mudstone layers, 1mm thick, are also present.

The LA also contains rare layers of silty-mudstone that average 20cm thick and fine-grained sandstone layers, 60 to 500cm thick, that average 220cm. Mud flasers are

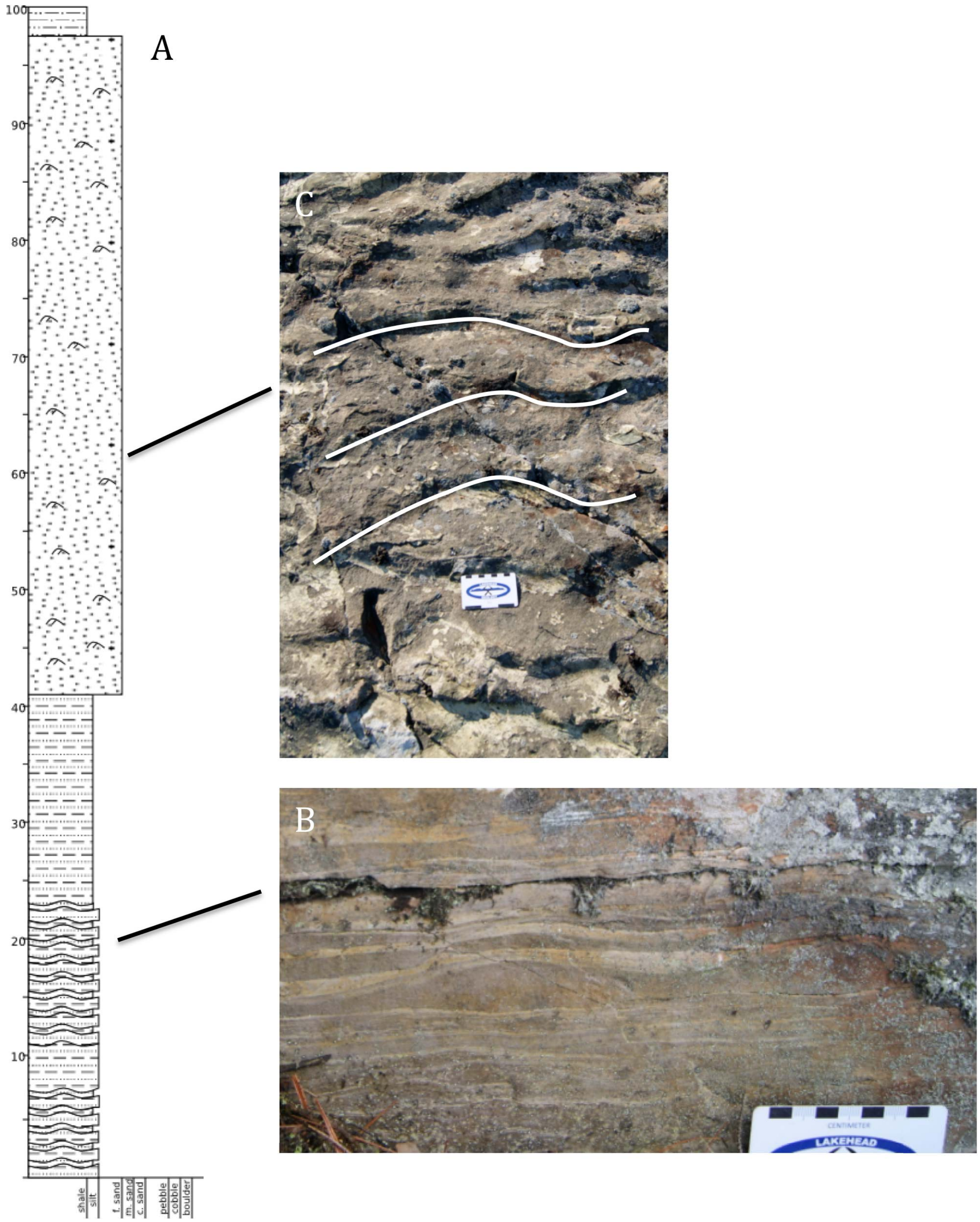


Figure 4.9 A) Data compiled from a number of small outcrops to make an overall stratigraphic column (scale in meters) of the Interlayered Siltstone and Fine-Grained Sandstone LA shown at the base of the stratigraphic column. The upper portion of the stratigraphic column is a representation of the Heterogeneous Sandstone LA that overlies the Interlayered Siltstone and Fine-Grained Sandstone LA in drill core. B) Wavy interlayered clay-rich siltstone and clay-poor siltstone to fine-grained sandstone. C) A bedding plane with current ripples, accentuated by the white lines, of the Heterogeneous Sandstone LA that is draped by mud.

present throughout the sand layers and range from 0.5 to 1cm thick and 2 to 30cm in length. Faint ripple cross-laminations are visible within the sand.

Within the drill core, the first 6.1m thick succession of this LA is mainly composed of silty-mudstone with some 0.1 to 5cm thick mud layers. The contacts between the two are sharp but irregular and loaded. There are no outsized clasts that appear in these layers, however; there are two layers of very coarse-grained sand that are 32 to 40cm thick. Small, angular rip-ups of the silty-mudstone appear within these sand layers. The upper 50cm of this succession have lenses of coarse-grained quartz-rich sand, 3 to 5mm thick and 2 to 3cm long.

The second succession of this LA is found approximately 32.6m stratigraphically below the start of the Lorraine Formation. It is composed of 25m of interlayered clay-rich and clay-poor sandstone. These layers range from 0.5 to 1cm thick whereas the less common mud layers range from 0.1 to 1.5cm thick. In addition, there are 5cm thick layers of fine-grained sandstone with sharp erosive contacts. There are also some contorted features within this layer that could be possible slump features.

4.4 Heterogeneous Sandstone Lithofacies Association

Outcrops of this LA within the Elliot Lake area are minimal but it is present stratigraphically above the Diamictite LA on Dunlop Lake. In this location, approximately 260m of cover separate the two LAs. In drill core it is stratigraphically above the Interlayered Siltstone and Fine-Grained Sandstone LA (Fig 4.9A).

On Dunlop Lake, the 23m thick outcrop that contains the best exposures is composed of medium-grained, quartz and feldspar-rich, pink sandstone with some coarse-grained sand dispersed throughout. Where the tops of bedding planes are visible, long and continuous current ripples are present (Fig. 4.9C). The ripples measure 3cm in height and 12cm from trough to trough with paleocurrents of 126° and 165°. In some cases, 1mm thick mud layers drape the tops of the ripples. The other outcrops of sandstone on the lake are composed of the same medium-grained pink sandstone although there are no visible sedimentary structures within them.

In the drill core, there is a gradual increase in the number and thickness of the pink, medium-grained sandstone layers upsection throughout the Diamictite LA. There is however the appearance of approximately 6.1m of the Interlayered Siltstone and Fine-Grained Sandstone LA prior to the 64m of the Heterogeneous Sandstone LA. The sandstone in drill core is composed of medium- to coarse-grained sand, which is quartz-rich and has a pink to light grey colour. The contact between the underlying Interlayered Siltstone and Fine-Grained Sandstone LA and the Heterogeneous Sandstone LA was missing due to the fact that core had been previously sampled however, there did appear to be a gradual decrease in clay content of the sandstone over the first 600cm that were visible. There is one 70cm thick layer of faint parallel lamination, found in the basal 27m of the LA along with rare 2mm thick mud layers. In the upper 36m of the LA, the sandstone becomes interlayered with some 30 to 200cm thick sections of interlayered sandstone, muddy-siltstone and mudstone. The muddy-siltstone is present as layers 0.5 to 1cm thick, while the mudstone layers are 1mm to 1.5cm thick. The medium-grained sandstone layers average 5cm thick with sharp but irregular erosive contacts. The last succession of the Heterogeneous Sandstone LA is located stratigraphically above another 25m of the Interlayered Siltstone and Fine-

Grained Sandstone LA, at the top of the Gowganda Formation. The final succession is 7.6m thick and is composed of muddy fine-grained sandstone with minor faint parallel laminations.

4.5 Quartz-Rich Sandstone Lithofacies Association

In outcrop, the transition from the upper succession of the Heterogeneous Sandstone LA into the Quartz-Rich Sandstone LA, of the basal Lorraine Formation, appears to be a gradual one with the clay content decreasing over the basal 5m. Overall, this LA is composed predominantly of medium- to coarse-grained sandstone layers that measure 74 to 200cm thick. A stratigraphic column of the LA is shown in Figure 4.9A. These layers commonly have horizons of planar cross-stratification approximately 20cm thick. The cross-stratification dips at approximately 20° in alternating directions producing paleocurrents of 70° and 140°. In addition, small horizons 1 to 4cm thick of current or wave ripples, accentuated by 1 mm thick mud drapes and flasers, are also present (Fig. 4.10B). Lenses of coarse-grained, feldspar-rich sand 4 to 5cm thick and 22 to 40cm long are common in this LA (Fig 4.10C).

Stratigraphically further up succession, the layers are predominantly composed of very coarse-grained sandstone and range from 5 to 40cm thick. There is evidence of faint large-scale planar cross-stratification as well as small scale ripple cross-lamination, again accentuated by thin 1mm thick mud drapes and flasers. In this portion of the succession, rare lenses 3 to 7mm thick and approximately 2m long of silty-mud are also present.

Nearly 120m of the Lorraine Formation was present in the drill core that was logged. The core was nearly all coarse- to very coarse-grained, quartz- and feldspar-rich sand. Minor ripple cross-laminations were present with 1 to 2mm thick mud drapes. Layers or lenses of very coarse-grained sand, 5-12cm thick, were also present.

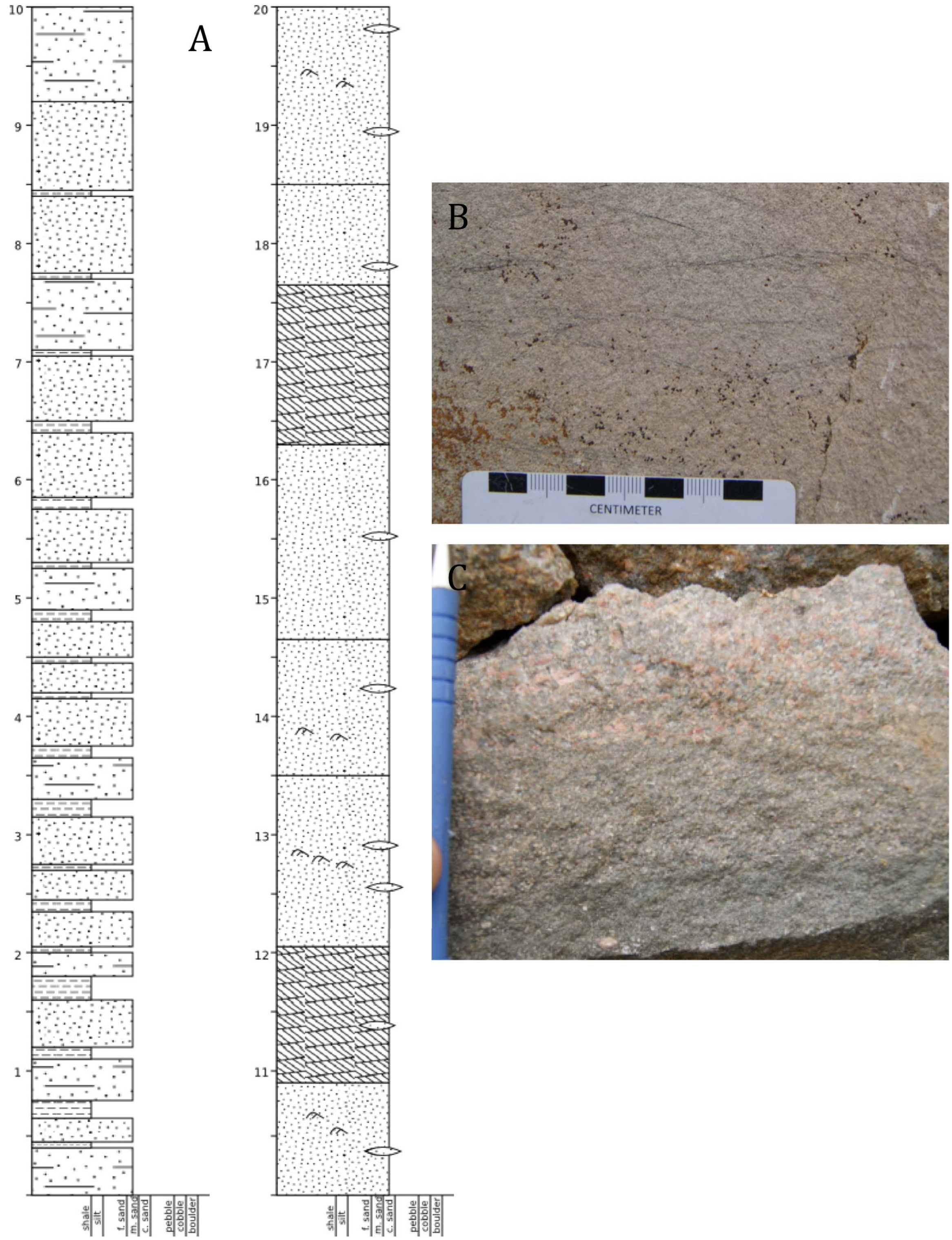


Figure 4.10 A) A stratigraphic column of the Quartz-Rich Sandstone LA on Dunlop Lake (scale in meters). B) Small horizons of current and wave ripples accentuated by mud drapes are common. C) Zones of coarse-grained feldspar-rich sand are common in this LA.

5. THESSALON STUDY AREA LITHOFACIES ASSOCIATIONS

Outcrop in the study area north of Thessalon, Ontario had bedding that was subhorizontal making it harder to get a continuous stratigraphic section through the entire Gowganda Formation. Outcrops were logged along Highway 129 north of the town of Thessalon as well as on Chub, Jobammageeshig and Wakomata Lakes (Fig 5.1). Thicknesses of the different sections and their stratigraphic positions relative to eachother were obtained from the map included in the Ontario Geological Survey's report on the area (Siemiatkowska & Douglas, 1973; Siemiatkowska, 1977). A general stratigraphic column for the area is shown in Figure 5.2. Data for the following lithofacies descriptions was compiled from these study locations.

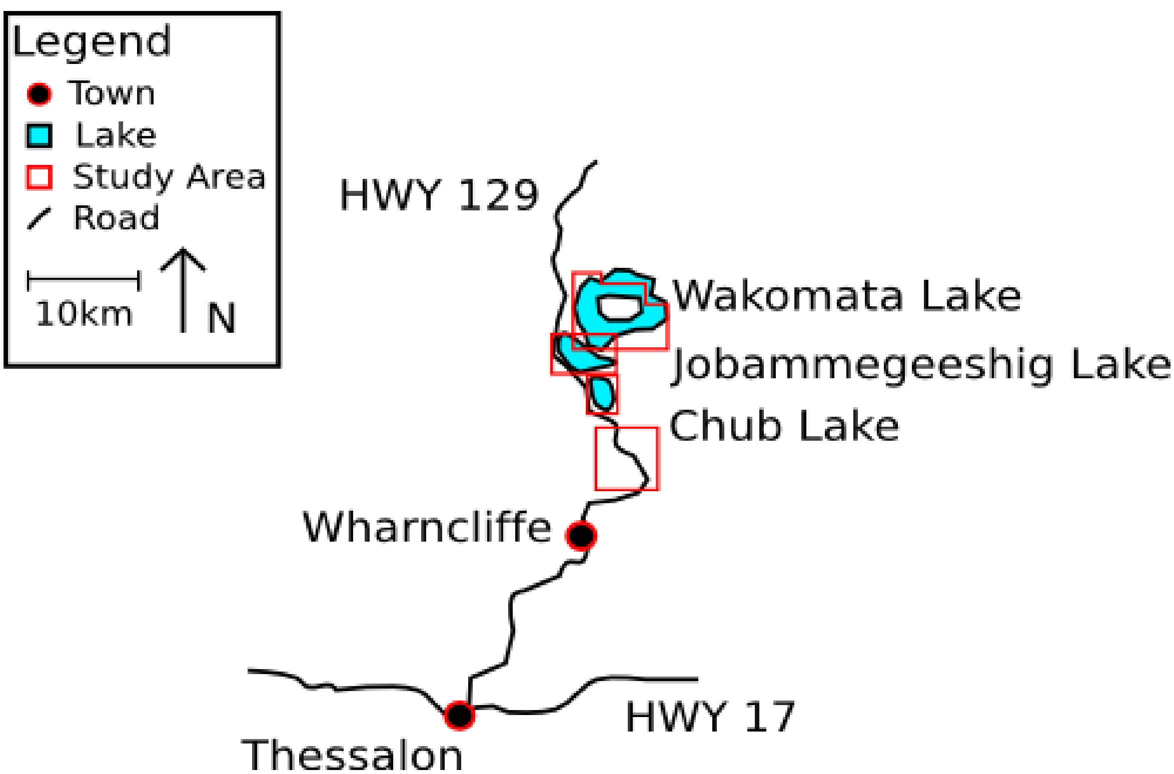


Figure 5.1 A map of the Thessalon study area showing the locations where outcrops were logged to compile stratigraphic columns of the area.

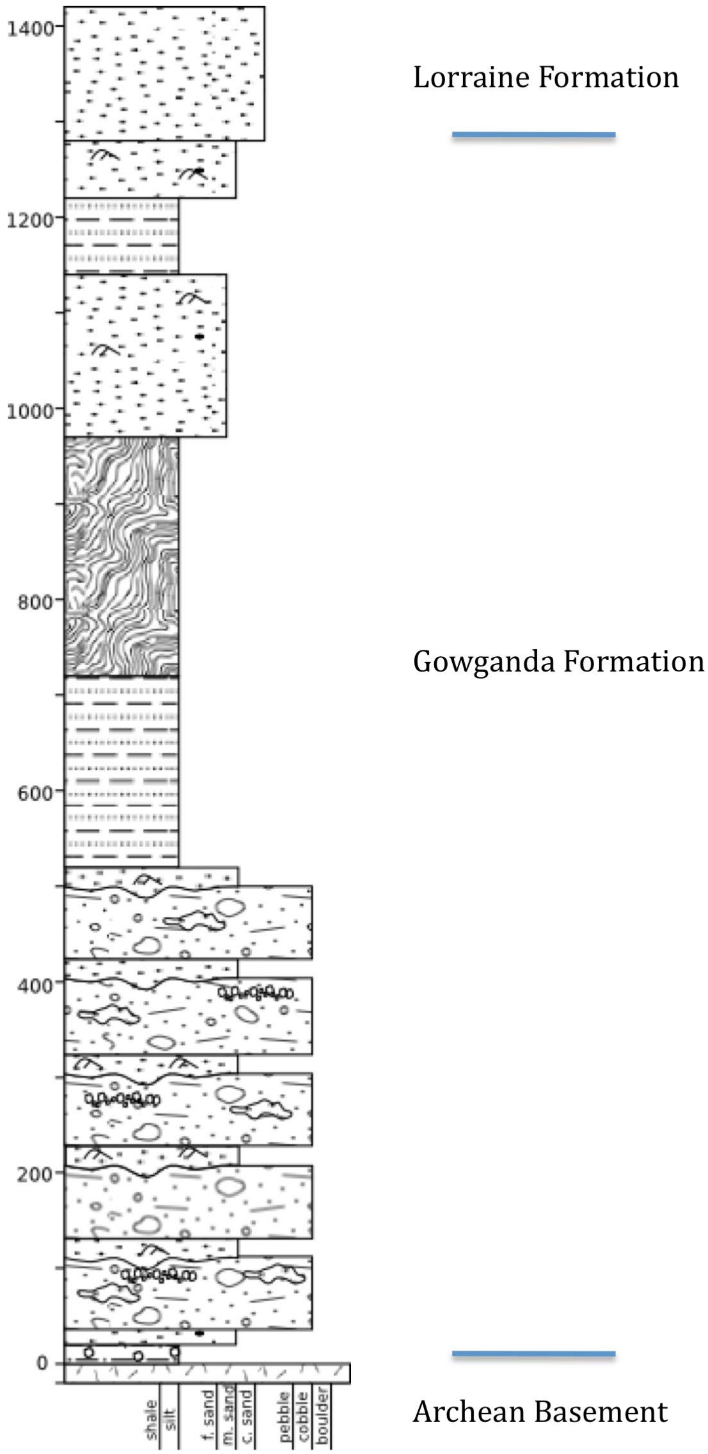


Figure 5.2 A general stratigraphic column of the Gowganda Formation in the study area north of Thessalon (scale in meters). Data from a number of outcrops was used to compile the overall column.

5.1 Diamictite Lithofacies Association

The basal contact of the Diamictite LA in the area north of Thessalon differs from the Espanola and Elliot Lake areas. It represents an unconformity, sitting directly on the granitic basement.

The lowest stratigraphic section of the LA logged was an abandoned quarry face off of Highway 129. This outcrop is composed of 0.6 to 1.0cm thick layers that often have sharp contacts and layers that grade from mud-rich silt to mud. The mud-rich silt layers or portions of the layers are 0.5 to 0.8cm thick whereas the mud layers or portions are 0.1 to 0.2cm thick. Granitic dropstones make up approximately 7 to 10% of the outcrop. They range in size from granules to cobbles and are commonly loaded into the underlying laminations (Fig. 5.3A). In addition, at the microscopic level, silt pellets approximately 2mm in diameter are present compressing underlying mud laminations (Fig. 5.3B). Lenses of poorly-sorted, clast-supported conglomerate composed of medium-grained sand to small pebbles, 0.2 to 1.5cm thick and 10 to 400cm in length, are also common within this outcrop. These lenses have sharp contacts with the adjacent siltstone layers and are rarely loaded into interlayering siltstones. Some of the sandstone layers also contain angular rip-ups of siltstone, 1 to 1.8cm in diameter, as well as small pebble-sized granite clasts (Fig. 5.4A). These thin sand lenses increase in frequency upsection towards the overlying massive, pink, medium-grained sandstone layer. The contact with the overlying sandstone layer is covered, although there is a sharp erosional ledge between the two lithologies indicating a possible sharp contact. On one cliff face in the quarry, a possible small slump block is present. The usually planar layers of the siltstone contain an erosive scour that is overlain by approximately 4.5cm of layers at a 30° angle to bedding. These angled layers are overlain by more planar graded layers (Fig. 4B).

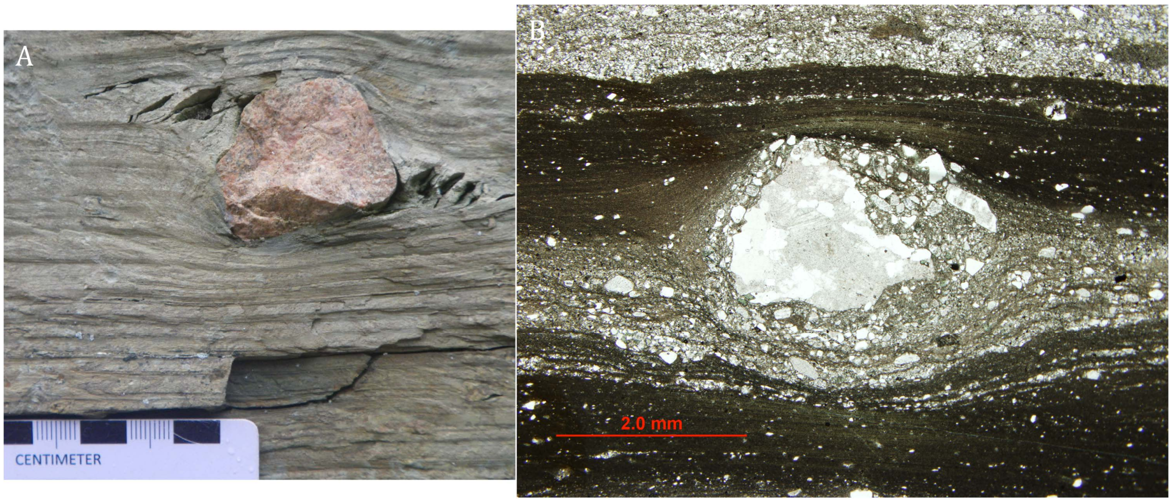


Figure 5.3 A) A granitic dropstone shown compressing underlying laminations in the Diamictite LA. B) A silt pellet, shown under the microscope in PPL, compressing laminations in silty-mud.

Stratigraphically upsection in the LA, the outcrops are composed predominantly of diamictite. The matrix of the diamictite is a muddy-siltstone with grains of medium- to very coarse-grained sand dispersed throughout. The majority of the outsized clasts are granitic in composition and range from subangular to subrounded. These clasts are granule- to boulder-sized with the largest measuring 43cm in diameter. Successions of interlayered pink, feldspar-rich, fine- to medium-grained sandstone and siltstone are present interbedded with the diamicite. These layers measure approximately 0.5 to 3.5cm thick and can be up to 2.5m long where they are in the form of lenses. Contacts with the adjacent diamictite matrix are either sharp or gradual and whispy. Soft sediment deformation and loading is common along the contacts between the sandstone and siltstone layers (Fig. 5.5A). In rare cases, the upper bedding planes of the sandstone layers show preserved

Figure 5.4 A) Lenses of poorly-sorted clast-supported conglomerate of medium-grained sand to small pebbles in the Diamictite LA. Angular rip-ups of siltstone (see arrow) are also common in these lenses. B) A possible slump block in the otherwise parallel laminated siltstone layers that is marked by erosive scours, accentuated by the white lines in B2.

wave ripples. In some cases, the sandstone is also present as contorted blobs within the matrix of the diamictite. In addition to these common, thinner layers and lenses of sandstone, sandstone layers and lenses up to 3.5m thick and 9.5m long are also present. The contact with the underlying diamictite layers is often gradational with a gradual decrease in the silt and mud content upsection. A large, angular rip-up of the diamictite matrix 1.2m long and 30 to 50cm thick is visible within one of these sandstone layers. The previously described thin, whispy sand layers appear to become more common upsection in the diamictite near the contact with an overlying thick sandstone layer. Dropstones are visible throughout these outcrops compressing underlying sand layers or interlayered sand and silt layers (Fig. 5.5B). In some cases, concentrated layers, 4 to 8cm thick, of granitic and siltstone clasts from pebble- to cobble-sized are present within the sand layers (Fig. 5.5C). Apart from these concentrated layers, outsized clasts are rare throughout the remainder of the sandstone layers and where present are granule- to small pebble-sized. Stringers one clast thick or small lag deposits are present within the diamictite layers and are commonly located at the basal contact of thick sandstone layers.

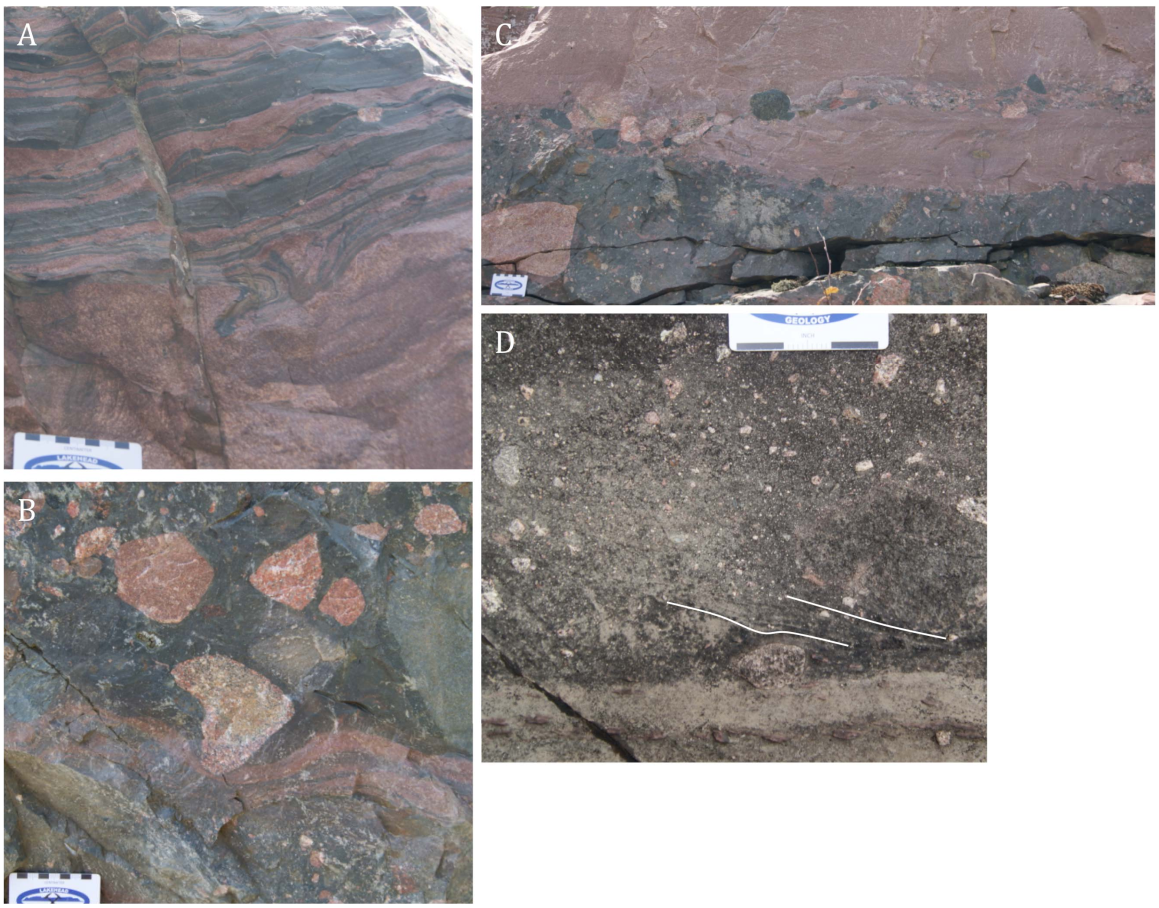


Figure 5.5 A) Soft sediment deformation and loading visible in interlayered sand and diamictite layers. B) Granitic dropstone compressing an underlying sandstone layer. C) A layer of concentrated outsized clasts in one of the sandstone layers. D) Clasts of red siltstone alligned at the base of the photo parallel to what is assumed to be a bedding plane. Faint cross-stratification is also present accentuated by the white lines.

Outcrops of the upper portion of the LA are present on Jobammageeshig Lake. The matrix of the diamictite in these outcrops is more sand-rich than the previously observed muddy-siltstone matrix. Outsized clasts are predominantly of granitic composition, although there are common angular clasts of red siltstone present. These clasts are aligned parallel to what is assumed to be bedding as well as along faint cross-stratification that is present in outcrops (Fig. 5.5D). One sand shadow was visible abutting an outsized clast. In addition to the siltstone clasts within the diamictite, one clast of iron formation 2.8 x 1.5cm was also present.

5.2 Interlayered Siltstone and Fine-Grained Sandstone Lithofacies Association

The contact between this LA and the underlying Diamictite LA is not visible, however the basal portion that was logged contained mud layers 0.1 to 0.2cm thick that were not present in the upper portion of the Diamictite LA. This indicates the contact between the two is possibly gradational. A stratigraphic column of the LA is shown in Figure 5.6A.

This LA is composed predominantly of siltstone layers, 0.3 to 7.0cm thick, with 1mm thick parallel laminations throughout (Fig. 5.6B). In the basal portion of the LA, some of these layers are graded from siltstone to silty-shale (Fig. 5.6C). These siltstone layers are interlayered with very rare fine-grained sandstone layers approximately 0.2mm thick. The upper portion of the LA however, contains numerous fine- to medium-grained sandstone layers 0.1 to 2.0cm thick. These layers are often continuous where visible and generally have current ripple cross-laminations within them. This creates a wavy appearance in the siltstone layers as the laminations drape over the rippled sandstone layers (Fig. 5.6D). The contacts between the sandstone and siltstone layers are sharp but have abundant loading structures. The balls and pillows

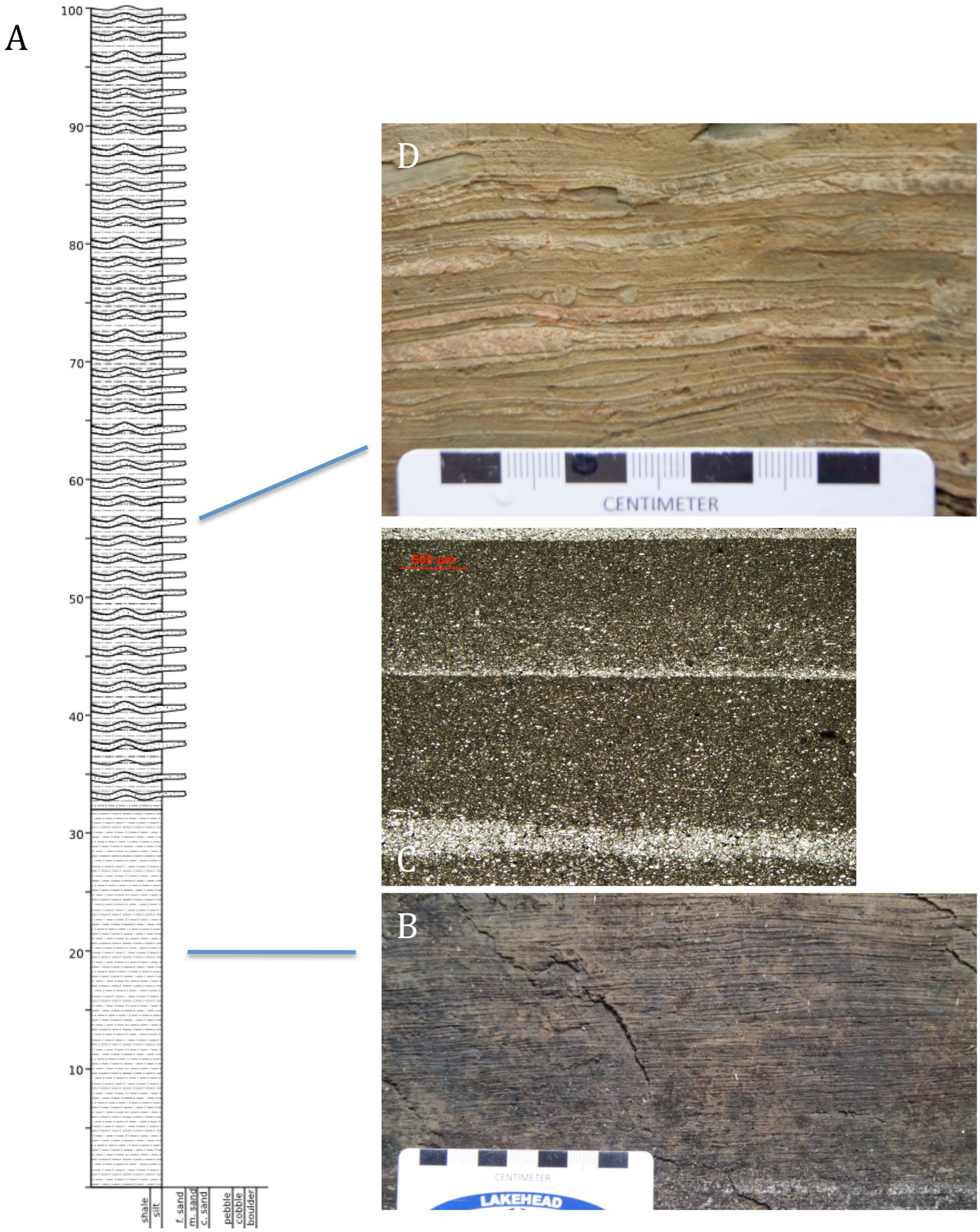


Figure 5.6 A) A stratigraphic column of the LA compiled from numerous outcrops in the study area (scale in meters). B) The LA is composed predominantly of parallel laminated siltstone. C) The siltstone can be normally graded from siltstone to silty-shale as shown here on the microscopic scale. D) The upper portion of the LA is composed of interlayered sandstone and siltstone and is commonly wavy bedded.

present commonly have remnant laminations within them. In two locations, large balls of interlayered sandstone and siltstone, roughly 5 to 8cm in diameter, are visible loading into an underlying siltstone layer.

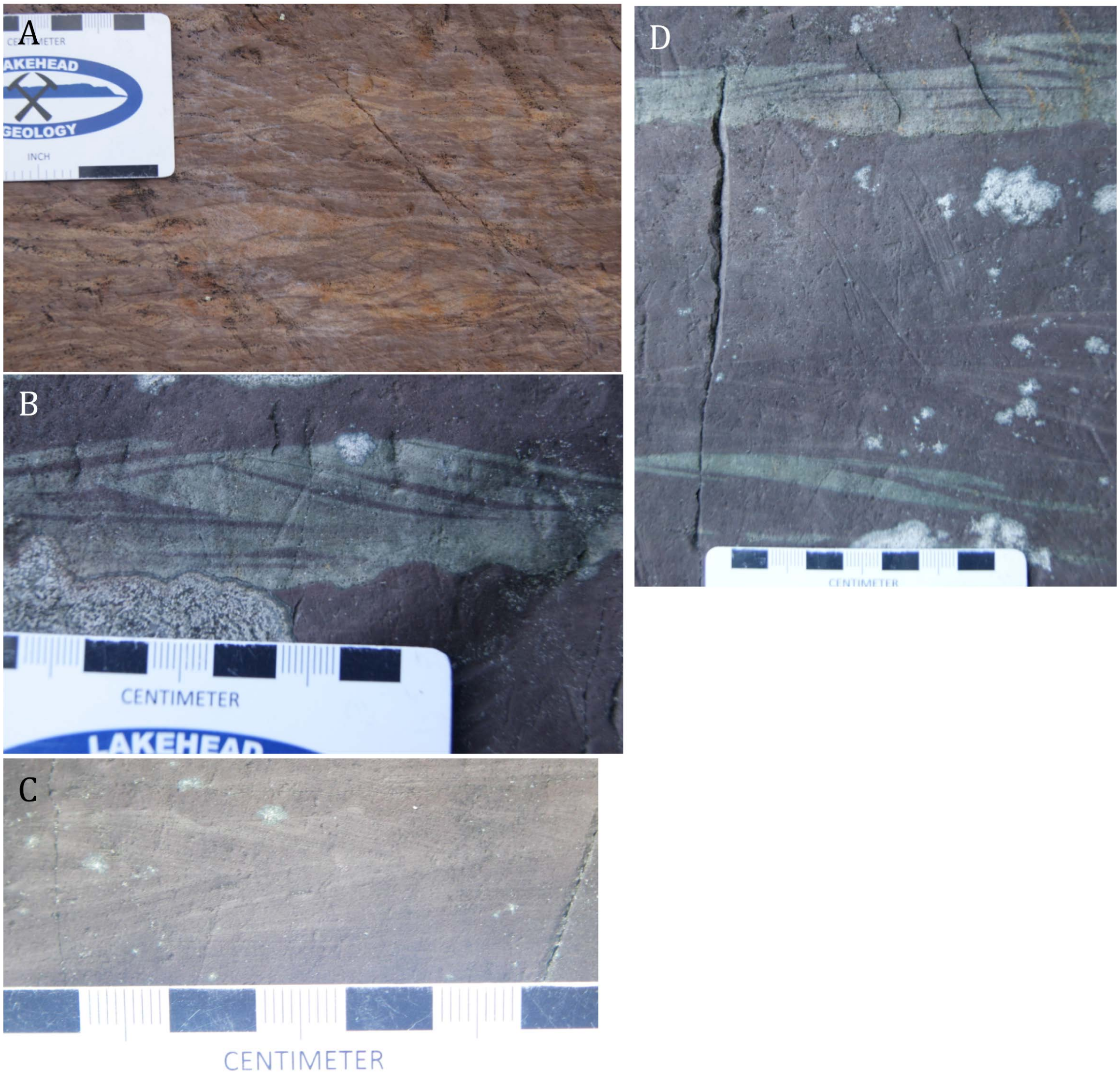


Figure 5.7 A) and B) Examples of wave ripples that are abundant in the purple-coloured succession of the LA. C) Small exposures of herringbone cross-stratification. D) Hummocky cross-stratification with the characteristic low-angle truncations.

On Lake Wakomata, there is an outcrop of the Interlayered Siltstone and Fine-Grained Sandstone LA that is composed of a purple siltstone. This second succession of the LA stratigraphically overlies the Heterogeneous Sandstone LA. Where visible, the contact between these two LAs is sharp and planar. The purple siltstone has abundant wave ripples 0.5 to 1.6cm in amplitude (Figs. 5.7A and 5.7B). In addition to the wave ripples, small exposures of herringbone cross-laminations (Fig. 5.7C) and hummocky cross-laminations (Fig. 5.7D) are present. The remainder of the outcrop is composed of either parallel laminated or massive siltstone.

This LA appears to be overlain by a succession of the Slump LA as well. The slumped siltstone in this location is composed of purple siltstone as opposed to the green-grey coloured siltstone of the first succession.

5.3 Slump Lithofacies Association

This LA is approximately 100m thick and is located stratigraphically overlying the Interlayered Siltstone and Fine-Grained Sandstone LA. It is composed of very contorted, chaotic-looking siltstone with elongate to rounded chunks of fine-grained sandstone (Fig. 5.8A). These chunks are angular to subrounded and in some cases appear to have remnant laminations visible within them. When elongate, the sand chunks average 1 to 8cm thick and 9 to 30cm long and when spherical, they average 6 to 20cm in diameter.

As previously mentioned, there is an additional outcrop, approximately 110cm thick, of the Slump LA associated with the purple coloured succession of the Interlayered Siltstone and Fine-Grained Sandstone LA. This slumped section is composed of highly contorted siltstone to very fine-grained sandstone layers that appear to have been interlayered with the purple siltstone layers. The contacts

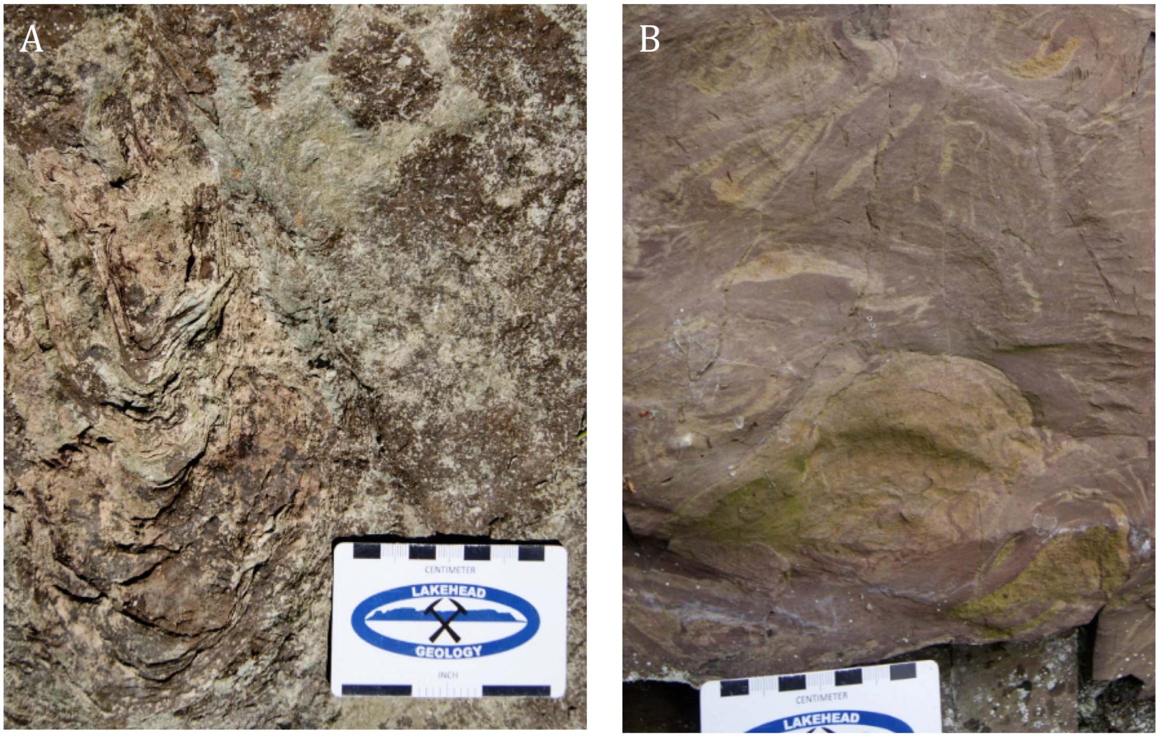


Figure 5.8 A) Very chaotic-looking siltstone with elongate to rounded, contorted chunks of sandstone. B) Highly contorted siltstone and fine-grained sandstone swirled throughout.

between the two layers are sharp with the very fine-grained sandstone present as 0.2 to 1.0cm thick layers or 8.0 to 15.0cm diameter rounded patches within the purple siltstone (Fig. 5.8B).

5.4 Heterogeneous Sandstone Lithofacies Association

The contact beween the underlying Slumped Siltstone LA and the Rippled Sandstone LA is not visible in outcrop in this region. The outcrops of this LA are found predominantly on Wakomata Lake approximately 42km north of Thessalon, Ontario. A stratigraphic column of the LA is shown in Figure 5.9A. In the visible basal portion of the LA, the sandstone layers range from 0.7 to 4.2m thick. They are composed mainly of massive, pink to salmon coloured, medium-grained sandstone. Some of the layers contain thin, 1mm thick, mud layers that are spaced approximately 0.2 to 0.8cm apart. In one location, these mud layers, which are parallel to bedding, are truncated by a mud layer that is at a 30° to the rest of the layers (Fig. 5.9B). This upper mud layer is overlain by a 4.2m thick layer of massive, medium-grained sandstone.

The next outcrop of the LA that is visible is composed mainly of massive, medium-grained, pink sandstone layers, 5.0 to 88.0cm thick, with bifurcating, symmetrical wave ripples on the bedding surfaces (Fig. 5.9C). These ripples are usually 9.0cm from crest to crest, however, there is one set that measures 22.0cm with slightly more rounded crests. The ripples measure approximately 1.7 to 2.0cm from trough to crest. The paleocurrents measured from these ripples are: 020°/200°, 115°/295°, 115°/295°, 130°/310° and 125°/305°.

In the uppermost visible portion of this LA, there are two layers of medium-grained sandstone with faint evidence of large-scale cross-stratification. A rough estimate of the paleocurrent at this location yielded measurements of approximately 015° and 025°.

An outcrop of medium-grained, pink sandstone is also visible stratigraphically underlying the Quartz-Rich Sandstone LA. The contacts with the underlying slumped purple siltstone as well as the overlying Quartz-Rich Sandstone LA are not visible. This outcrop is composed of layers of massive sandstone that range from 30 to 50cm and contain no visible interlayered shale.

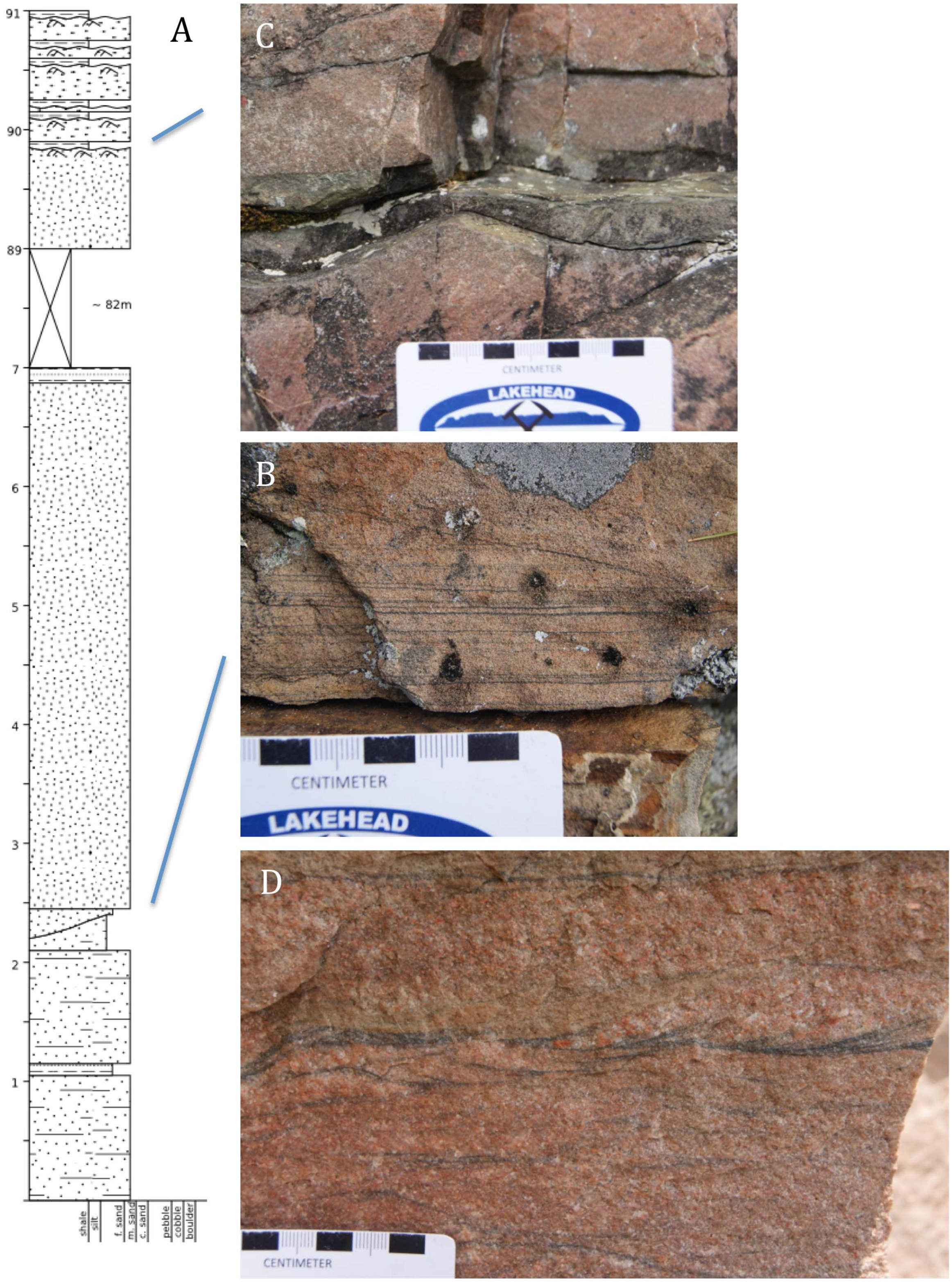


Figure 5.9 A) A stratigraphic column compiled from outcrops logged on Wakomata Lake of the Heterogeneous Sandstone LA (scale in meters). B) Interlayered sandstone and thin clay layers and a truncated surface also marked by a clay layer. C) Wave ripples, common in the upper portion of the LA, overlain by a clay layer. D) Wave ripples in the Quartz-Rich Sandstone LA of the Lorraine Formation accentuated by clay drapes at the tails of the ripples.

5.5 Quartz-Rich Sandstone Lithofacies Association

As previously mentioned, the contact between the underlying outcrop of medium-grained, pink, massive sandstone and the Quartz-rich Sandstone LA of the Lorraine Formations is not visible on Wakomata Lake. The initial outcrop of the LA is composed of siltstone layers, 12 to 30cm thick, interlayered with medium-grained, pink sandstone layers, 40 to 150cm thick, with some coarse- to very coarse-grained sand grains dispersed throughout. The similaritites in the composition of the sandstone in this LA and in the underlying Heterogeneous Sandstone LA indicate it is likely that the contact betweent the two LAs is a gradual one. The layers of medium-grained sandstone with coarse to very coarse grains in this LA contain faint cross-stratification as well as lenses of coarse- to very coarse-grained sand 0.5 to 0.8cm thick. The basal contact of the siltstone layers is gradual. However, the upper contact from siltstone to sandstone is sharp. These appear as graded tops on the sandstone layers.

Following approximately 94m of cover, the next outcrop of the Quartz-Rich Sandstone LA is again composed predominantly of medium- to coarse-grained sandstone with large-scale cross-stratification that appear to be planar, are approximately 30 to 50cm thick, and dipping between 25° and 30°. Measurements of the paleocurrent taken from these structures were 000° and 030°. In addition to the cross-stratification, wave ripple laminations 0.4 to 2.0cm thick are present. They are accentuated by 1mm thick clay drapes visible on the ripple tails (Fig. 5.9D). Lenses of coarse- to very coarse-grained sand 2 to 12cm thick and 30 to 200cm long are also present in the sandstone as well as rare 1mm thick clay layers.

The last visible outcrop of the Lorraine Formation's Quartz-rich Sandstone LA was approximately 385m stratigraphically above the previous one. The sandstone is coarse- to very coarse-grained, quartz-rich, with common granule- to small pebble-sized clasts of quartz and feldspar that can be arranged as stringers. Rare, subangular, red clasts 0.5 to 1.5cm in diameter are also present within the sandstone. These clasts are likely jasper as the outcrop has a similar appearance to the commonly named "Puddingstone" that is prevalent in the region. Faint large-scale cross-stratification is visible within the 40cm thick outcrop and suggests a paleocurrent roughly to the east.

6. COBALT STUDY AREA LITHOFACIES ASSOCIATIONS

A map of the Cobalt study area with the locations where outcrops were logged is shown in Figure 6.1A. The drill core used in the Cobalt area was from holes TME-07-02 (Zone 17 0554028E 5288249N), TME-07-03 (Zone 17 0554027E 5288276N) and TME-08-17 (Zone 17 0554331E 5287559N) that were drilled in 2007 and 2008 by Temex Resources Corp.

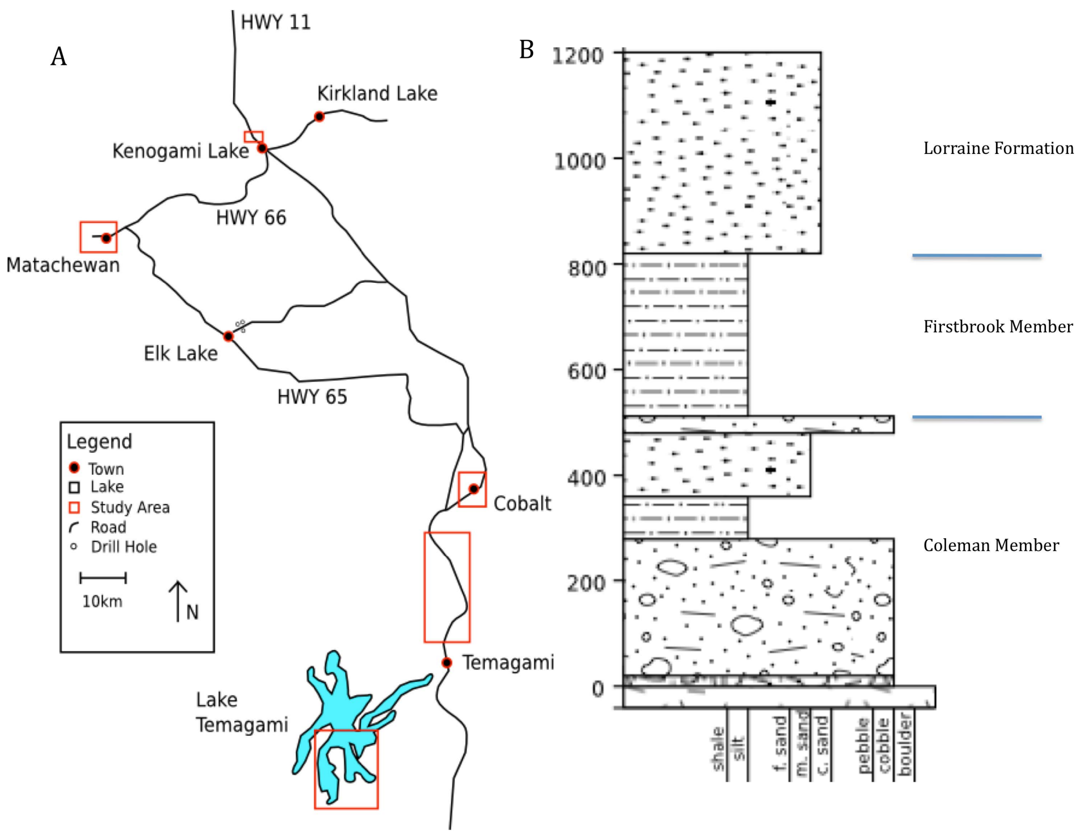


Figure 6.1 A) A map of the Cobalt study area showing the locations where outcrops were logged to compile stratigraphic columns of the area. The drill holes were located to the northeast of Elk Lake (black circles). B) A general stratigraphic column (scale is in meters) of the Gowganda Formation. The lowermost portion is called the Coleman Member while the upper portion is called the Firstbrook Member. The Firstbrook Member is overlain by the sandstones of the Lorraine Formation.

In the northern-most region of study, the Gowganda Formation is historically divided into the basal Coleman Member and the upper Firstbrook Member. The Coleman Member is composed of a basal breccia and interlayered diamictite, clast-supported conglomerate, sandstone and laminated siltstone layers. The Firstbrook Member is similar to the laminated siltstones of the Coleman member. However, they take on more of a brownish-purple colour in contrast to the greenish-grey of the Coleman. In addition, the laminated siltstones of the Firstbrook Member do not contain dropstones whereas the Coleman member does. A general stratigraphic column of the study area is shown in Figure 6.1B.

6.1 Basal Breccia Lithofacies Association

The basal unconformity of the Gowganda Formation is composed of the Basal Breccia LA that sits on the underlying rocks of the Archean. The contact between the two lithologies is sharp but irregular and where visible the brecciated layer is approximately 50 to 150cm thick.

In the exposures of the LA on Nipissing Hill in Cobalt, Ontario, the breccia is composed of angular clasts that range from 0.5 to 80.0cm in diameter (Fig. 6.2). These clasts are composed of granite as well as the underlying Archean basalts. The breccia is visible as irregular shaped patches within the basalts suggesting it filled in topographic lows in the Paleoproterozoic paleotopography. There is a gradual contact between the breccia and the overlying diamictite. The diamictite visible at this location is composed of a muddy-siltstone matrix with approximately 10% granitic clasts. The clasts, grey to white in colour, are mainly subangular to subrounded and range in size from granules to small cobbles, the largest measuring approximately 10cm in diameter. The matrix appears to be thinly laminated with layers 1 to 2mm thick.

Figure 6.2 The Basal Breccia that is composed of grey to white coloured, angular clasts of granite and the underlying Archean basalts in a muddy-siltstone matrix.

Approximately 22km southwest of the Cobalt region, outcrops of the Basal Breccia LA are visible (Smyk et al., 1997). In this location, the breccia is again composed of angular fragments of the underlying Archean granitic and metamorphosed basaltic rocks. The matrix is laminated muddy-siltstone and appears to be draping over and filling in spaces between clasts (Smyk et al., 1997).

The basal contact between the Gowganda Formation and the underlying Archean rocks is also visible to the north along Highway 11, north of Kenogami, Ontario. The contact is again sharp and irregular in this location. However, no Basal Breccia LA is present.

In drill core obtained from northeast of Elk Lake, Ontario, northwest of the Cobalt region, the unconformity between the Gowganda Formation and the underlying Archean rocks is marked by approximately 1m of breccia. The angular clasts range from 1 to 20cm in diameter within a muddy-siltstone matrix. The clasts are mainly of granitic composition however, medium-grained sand to granule-sized clasts of quartz and feldspar are also present.

6.2 Diamictite Lithofacies Association

The outcrops of the Diamictite LA throughout this region were often small with near horizontal bedding, making it difficult to obtain an overall thickness of many of the layers. The drill core obtained from near Elk Lake, Ontario, was a valuable asset, providing thicknesses as well as more complete views of the layers. Three stratigraphic columns are shown in Figure 6.3 giving an overall idea of the interbedding of diamictite, poorly-sorted matrix-supported conglomerate composed of sand- to boulder-sized clasts, sandstone and siltstone layers in the Diamictite LA. Lateral correlations between the drill holes were not possible attesting to the complexity of the interbedding of the layers.

In the drill core, the diamictite layers range from 1 to 28m with an average thickness of 7m. These layers are composed of a muddy-siltstone matrix with sand grains distributed throughout and 10% to 15% clasts that range in size from granules to boulders. The clasts are subrounded to subangular and are most often of granitic composition (Fig. 6.4A). Although the matrix is commonly massive, there

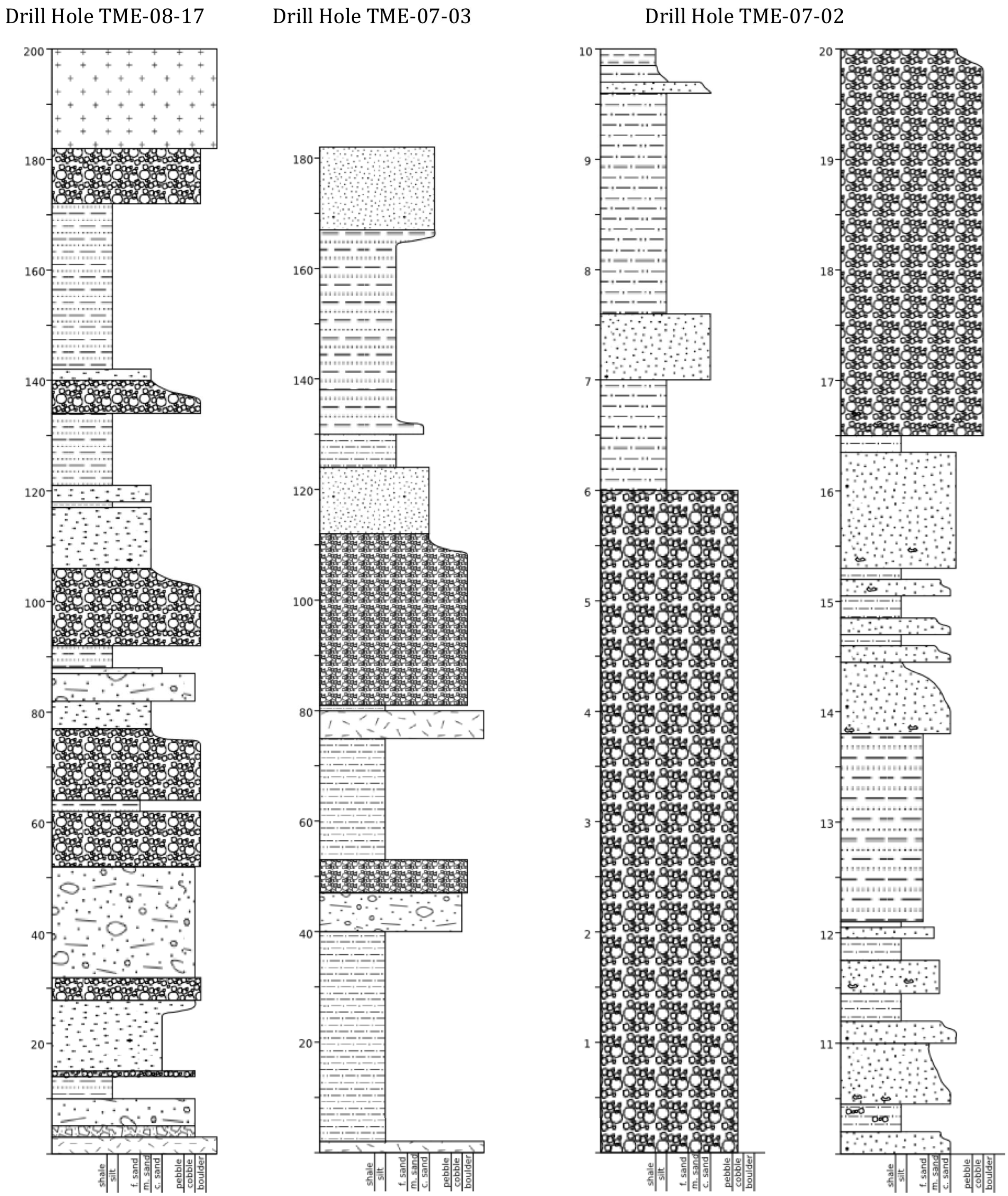


Figure 6.3 Detailed stratigraphic columns (scale is in meters) of interlayered diamictite, poorly-sorted matrix-supported conglomerate composed of sand- to boulder-sized clasts, sandstone and siltstone layers of the Diamictite LA.

are horizons of faintly laminated siltstone. In addition to the laminated siltstone, thin layers or lenses of fine- to medium-grained sandstone are also present. Rarely, these layers are graded from sand to silt.

The stratigraphic columns compiled from the drill core show an interbedding of diamictite, poorly sorted matrix-supported conglomerate, sandstone and laminated siltstone layers. The diamictite layers often have gradual upper and lower contacts with adjacent siltstone layers while the contacts with the sandstone and conglomerate layers are sharp.

The layers of poorly sorted matrix-supported conglomerate measure 1 to 30m in thickness, and average 12.5m. These layers are composed of 25% to 40% clasts with a matrix of predominantly medium- to coarse-grained sand and minor siltstone. The clasts are granule- to boulder-sized, subrounded to subangular and are once again mainly granitic in composition (Fig. 6.4C). However, there are common sub-angular siltstone clasts or rip-ups that measure 1 to 4cm in length (Fig. 6.4B). The contacts between the poorly sorted matrix-supported conglomerate and the laminated siltstone and diamictite are sharp. However, the contacts with adjacent sandstone layers are most often gradual.

The sections of sandstone present within the Diamictite LA were best seen in the drill core and ranged from 1 to 27m thick, averaging 12m in thickness. The layers measure 5 to 150cm thick and were either well sorted sandstones or moderately sorted pebbly sandstones. The sandstones were commonly normally graded from very coarse- to medium- or fine-grained sandstone (Fig. 6.4D). However, where the sandstone layers grade into an overlying layer of the poorly sorted, matrix-supported conglomerate they became a reverse graded basal portion of the conglomerate. The well-sorted sandstone layers have parallel laminations as well as cross-stratification. The cross-stratification dips between 10° and 30°. Symmetrical ripples are also common in the sandstone layers and, asymmetrical ones are present, but are rare. These ripples are a maximum of 1.5cm in amplitude. Rare granite clasts up to a maximum of 8cm in diameter are present in the sandstone layers. Rip-ups of siltstone are present in the basal portions of some sandstone layers.

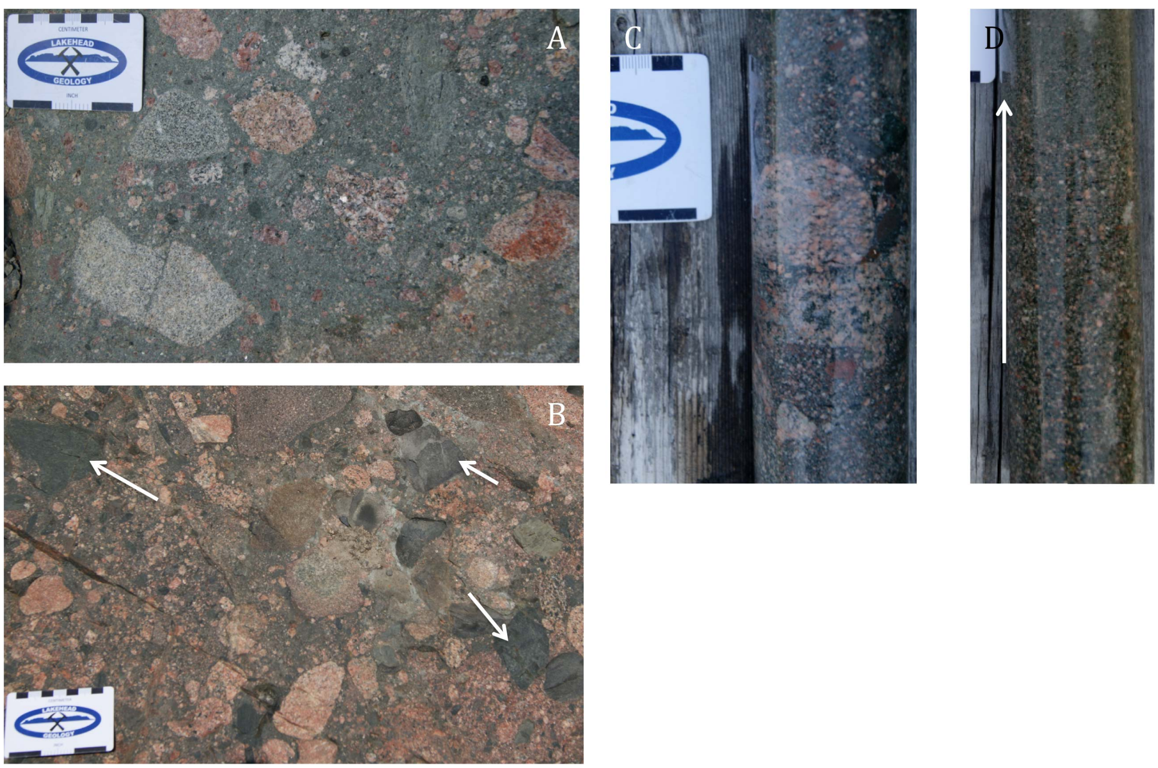


Figure 6.4 A) Diamictite in outcrop composed of a muddy-siltstone matrix with sand grains distributed throughout. The granule- to boulder-sized clasts are subrounded to subangular and are most often of granitic composition. B) In outcrop, common sub-angular siltstone clasts or rip-ups are present (indicated by the arrows). C) Poorly-sorted, matrix-supported conglomerate with granule- to boulder-sized clasts mainly granitic in composition. The matrix is composed of medium- to coarse-grained sand with minor siltstone. D) Sandstone normally graded from very coarse- to medium-grained sandstone.

The outcrops of diamictite in and around the town of Cobalt, Ontario, southeast of Elk Lake, had some interesting features. As previously mentioned, the diamictite here overlies the basal breccia making it the basal portion of the Gowganda Formation. The clasts in this region range from small pebbles to boulders, as large as 1.5m in diameter, and are predominantly of granitic composition. Some of the larger clasts are fractured and have muddy-siltstone matrix, along with outsized clasts, within the cracks (Fig. 6.5A). In one outcrop, concentric rings of laminated siltstone are visible around the clasts (Fig. 6.5B). In many of the outcrops, irregular shaped clast-rich patches, up to approximately 1m in diameter, containing 60% to 70% clasts are common. Irregular shaped patches of fine- to medium-grained sandstone, 2 to 20cm thick and 30 to 300cm long are also present. These sand patches have some possible faint symmetrical ripples present. Layers of coarse- to very coarse-grained sand 5 to 17cm thick, that are continuous over the outcrop width of 15m, show some grading in the basal portion of the layers. Dropstones penetrate these layers.

Approximately 40km south of Cobalt, on Lake Temagami, Ontario, the visible outcrops of diamictite are similar to those in the north. They are composed of muddy-siltstone matrix and 25% to 30% subangular to subrounded granitic clasts. One clast of laminated siltstone, measuring 16x40cm, was observed. Diamictite outcrops along Highway 11, just north of Temagami, contain large, clast-rich lenses, 5 to 150cm thick, and 40 to 600cm long where visible.

Outcrops of the Diamictite LA in Matachewan, Ontario, located roughly 30km northwest of Elk Lake are composed predominantly of a clast-supported conglomerate. These outcrops are 85% to 90% clasts with a matrix of coarse- to very coarse-grained sand. In addition to the granitic clasts, there is a large portion of angular siltstone clasts measuring 0.5 to 25cm. The conglomerate, approximately 1 to 1.5m thick, is interlayered with a red siltstone layer that measures 0.8 to 1cm thick where visible. The uppermost portion of the outcrop is composed of a medium-grained sandstone layer that also measures 0.8 to 1cm thick where visible. The conglomerate appears to grade into the sandstone layer with a progressive decrease in the number of clasts and the overall grain size.

Unlike the other outcrops of the basal unconformity of the Gowganda Formation, the Basal Breccia LA is not present at the contact near Kenogami, Ontario. This outcrop is dominated by the clast-rich diamictite layers that are interlayered with coarse- to very coarse-grained sandstone layers. Clasts that range from granule- to boulder-sized are common within the sandstone layers. In one location, faint parallel laminations are present. The contacts between the sandstone and diamictite layers can be sharp, with common injection features, or gradual. Outcrops of the diamictite to the north of Kenogami, Ontario, along Highway 11, have abundant lenses of red, medium-grained sandstone that measure 5 to 30cm thick and 30 to 200cm long. These lenses take on a whispy appearance as their contacts with the diamictite are gradational. Outsized clasts of granite are also present within the sand lenses.

Layers of laminated, greenish-grey coloured siltstone comprise a large portion of the Coleman Member. Alternating layers of siltstone, 1 to 2cm thick, and silty-mudstone or mudstone 0.3 to 0.7cm thick are common. The majority of these

Figure 6.5 A) Boulder-sized clast fractured with muddy-siltstone matrix and outsized clasts present within the cracks. B) Concentric rings of laminated siltstone surrounding a granitic outsized clast within a diamictite layer. C) Graded layers from fine-grained sand or silt to mud (arrows).

layers have 1mm thick parallel laminations. However, successions 2 to 100cm thick, of symmetrical ripples are also present. These ripples have maximum amplitude of 2cm and measure 1 to 5cm from crest to crest. Thin layers and lenses of fine- to coarse-grained sandstone, 0.3 to 1cm thick, are present in the laminated siltstone. These layers were commonly loaded into the underlying silt or mud layers. Planar cross-laminations are common within the sandstone layers and are present in some areas within the siltstone layers. They yielded paleocurrents that measure approximately

180° and 30°. These measurements provide general paleocurrent measurements of southward and northeastward. In outcrop near the Little Silver Vein, Cobalt Ontario, subangular to subrounded granule- to cobble-sized dropstones are common within the laminated siltstone sections. They compress underlying laminations. Some graded layers that measure a maximum of 2cm were also observed within the laminated portions of the LA. These layers grade from fine-grained sand or silt to mud (Fig. 6.5C).

In the drill core obtained from near Elk Lake, Ontario, additional features such as gradual contacts between the laminated siltstone and thicker sandstone layers are common. These contacts are characterized by sections of interlayered siltstone, 1 to 8cm thick, and fine- to coarse-grained sandstone layers, 4 to 16cm thick. Contacts between the individual siltstone and sandstone layers themselves are often sharp, with approximately 5x5mm siltstone rip-ups common within the sandstone layers. Cross-stratification within these successions, dipping 30°, is also common. Rare zones of brecciated laminated siltstone and mudstone that appears to be characteristic of slumping are present. Dropstones of granule- to cobble-size are also visible within the laminated siltstone sections of the drill core.

In outcrop on Lake Temagami, the laminated siltstone commonly is interlayered with layers of diamictite. Although the siltstone that forms the matrix of the diamictite and the laminated siltstone are of similar compositions, the layers have sharp but irregular vertical contacts where the laminations suddenly appear or disappear. Small dropstones are present in some of these laminated outcrops ranging in size from 0.5 to 1cm in diameter. A possible slumped area, composed of contorted chunks of fine-grained sandstone 2 to 15cm thick and 2 to 20 cm long within a siltstone matrix, is present on the eastern side of the southwest arm of Lake Temagami. Granule- to cobble-sized granite clasts are also present within these outcrops. Brecciated fragments of interlayered siltstone and sandstone are also present on Lake Temagami (Simony, 1964). These fragments are commonly contorted or rolled within a siltstone matrix appearing to be soft-sediment deformation that occurred in a possible slump event. Granite pebbles are present in these outcrops as well (Simony, 1964).

In one outcrop on Lake Temagami, layers of medium- to fine-grained sandstone, averaging 54cm in thickness, are interlayered with siltstone layers, averaging 56cm in thickness (Fig. 6.6A). Both the sandstone and siltstone layers are parallel laminated as well as low-angle, planar cross-stratified. Wave ripples were present in the upper 6cm of one sandstone layer (Fig. 6.6B). The siltstone layers have lenses of medium-grained sandstone, 4 to 5cm thick and 20 to 140cm long, within them, as well as rare rounded balls of medium- to fine-grained sandstone. These sandstone balls are of the same composition as the adjacent sandstone layers and occur in the basal 10cm of two siltstone layers (Fig. 6.6C). There is a sharp upper contact to these siltstone layers and they are overlain by planar cross-stratified siltstone. The layers of sandstone and siltstone pinch and swell, reaching a minimum thickness of 1cm in some cases however, they are continuous over the entire outcrop of approximately 30m. Granitic dropstones that are compressing underlying laminations are present in this outcrop (Fig. 6.6D).

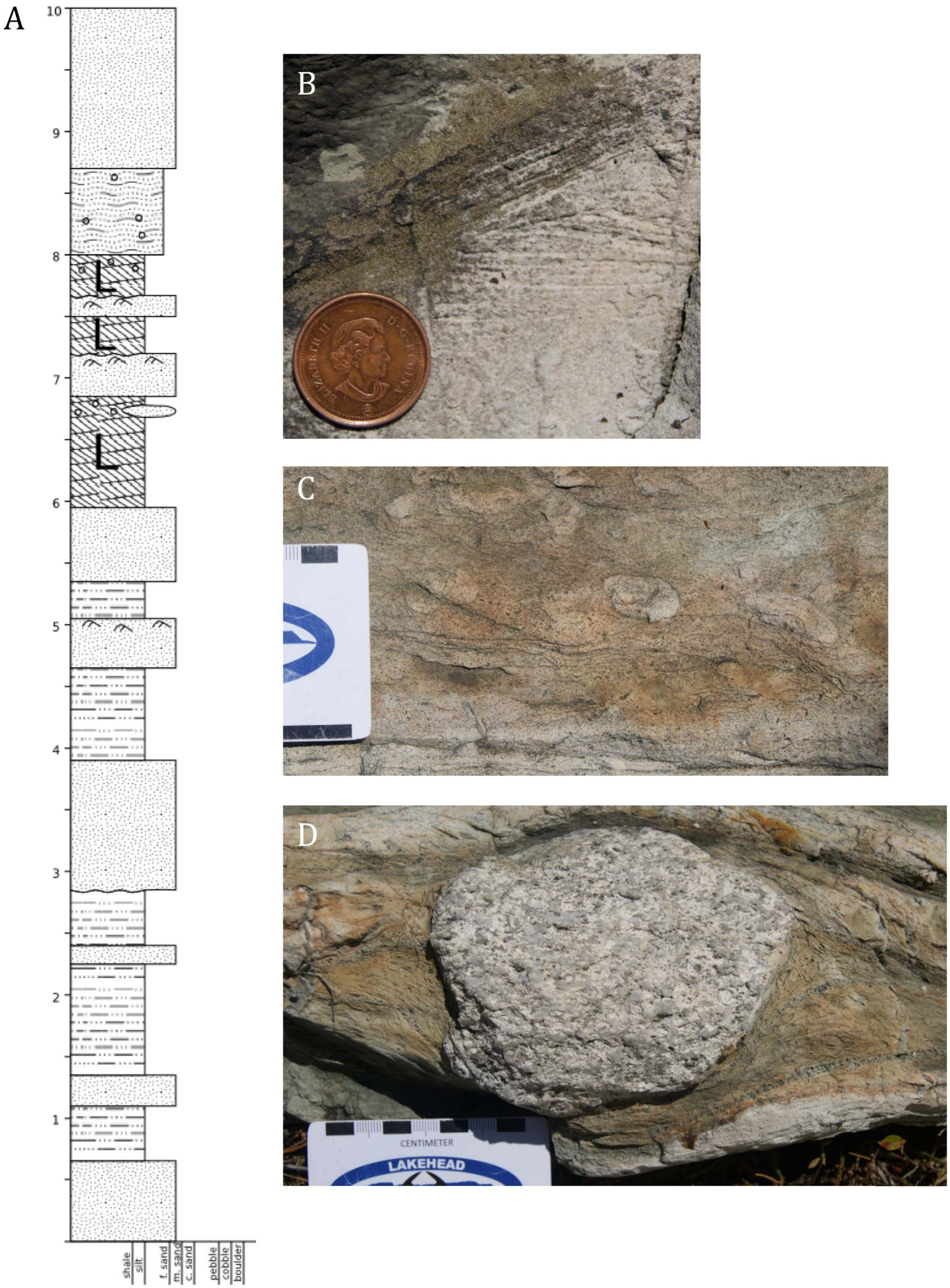


Figure 6.6 A) A detailed stratigraphic column of an interlayered sandstone and siltstone outcrop on Lake Temagami, ON. This outcrop is interpreted to be incorporated into the overall Diamictite LA. B) Wave ripples present in the upper 6cm of one sandstone layer. C) Rounded balls of medium- to fine-grained sandstone in a sandstone matrix of similar composition. D) Granitic dropstone compressing underlying laminations.

6.3 Interlayered Siltstone and Fine-Grained Sandstone Lithofacies Association

The Interlayered Siltstone and Fine-Grained Sandstone LA correlates to the upper portion of the Gowganda Formation historically named the Firstbrook Member in this study area. Outcrops of this LA are a brownish-purple colour and are located along Highway 11, south of Cobalt, Ontario. These layers are composed of interlayered siltstone, fine-grained sandstone and mudstone layers that range from 0.2 to 6.0cm thick. Layers 1 to 4cm thick are commonly graded from siltstone to mudstone and occur in sets of two to four layers (Fig. 6.7A). The sandstone layers commonly pinch and swell. These thicker zones of the sandstone layers, 0.5cm thick and 2 to 5cm long, have abundant current ripple cross-laminations (Fig. 6.7A). The paleocurrents obtained from these cross-laminations were not extremely accurate but were roughly bidirectional to the north and south. Alternatively, the sandstone layers can be parallel laminated or massive with symmetrical ripples on the upper bedding plane. The ripples have maximum amplitude of 2cm but are most commonly approximately 1cm from trough to crest. No dropstones were visible in this LA. The contact between these laminated siltstones and the underlying laminated siltstones of the Coleman Member are thought to be gradational (Mackean, 1968).

6.4 Quartz-Rich Sandstone Lithofacies Association

In the Cobalt region, the outcrops of the Quartx-Rich Sandstone LA that correspond to the basal portion of the Lorraine Formation, are predominantly a medium- to very coarse-grained quartz-rich sandstone with minor feldspathic content. Large-scale trough cross-stratification, as well as some areas of planar cross-stratification are present in outcrops along Highway 11, south of Cobalt (Figs. 6.7B and 6.7C). Soft sediment deformation was documented by Donaldson (1982)

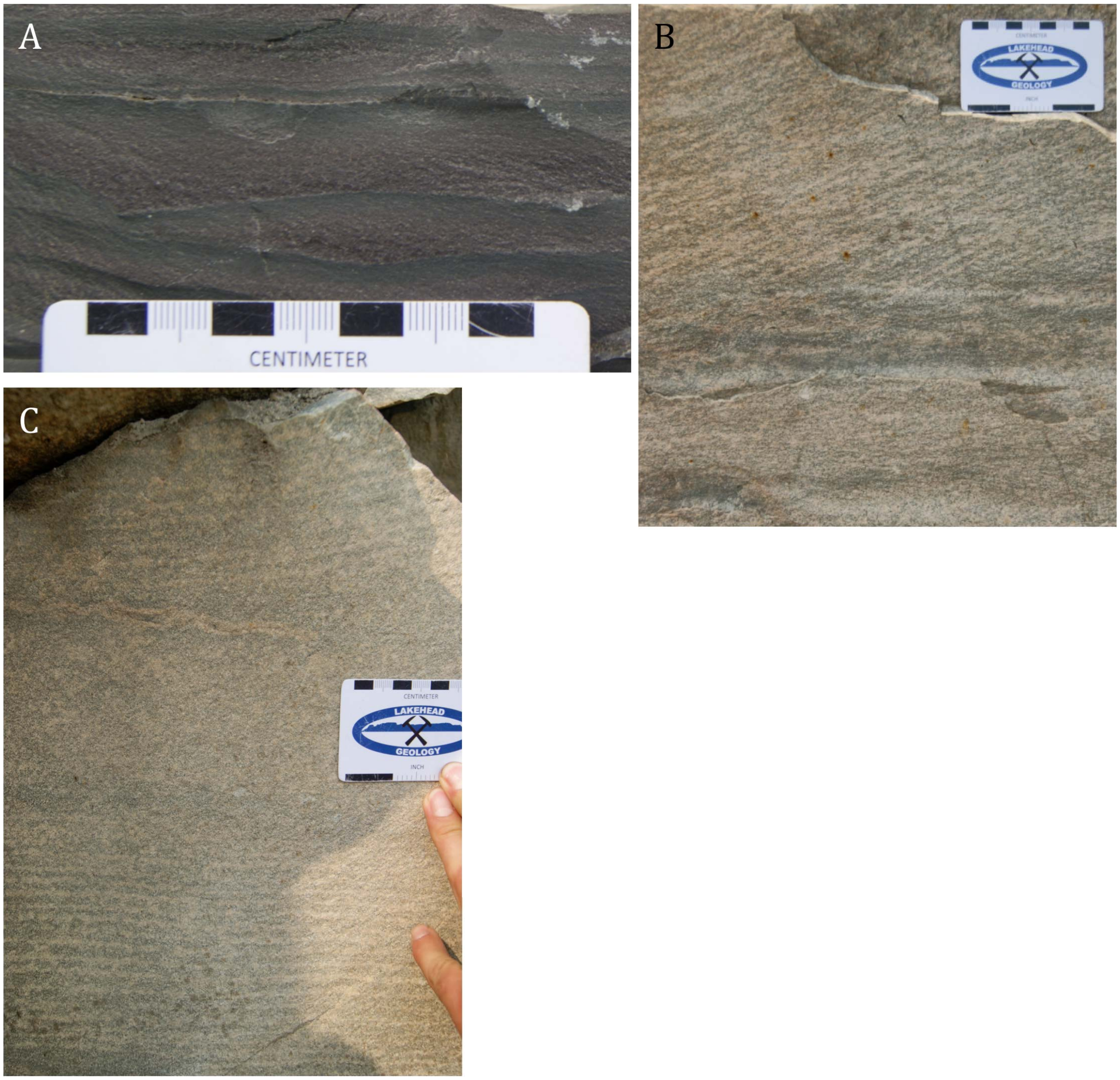


Figure 6.7 A) Layers graded from siltstone to mudstone in the Interlayered Siltstone and Fine-Grained Sandstone LA. The layers have faint current ripple cross-laminations present. B) Planar cross-stratification present in the medium- to very coarse-grained quartz-rich sandstone of the Quartz-Rich Sandstone LA. C) Large-scale trough cross-stratification is common in the Quartz-Rich Sandstone LA.

although this was not observed during fieldwork for this thesis. Outcrops of the Quartz-Rich Sandstone LA along the west shore of the northern arm of Lake Temagami also show evidence of cross-stratification (Simony, 1964). All descriptions of the Lorraine Formation in the northern study area indicate there is a gradual transition from the underlying laminated siltstones of the Gowganda Formation to the quartz-rich sandstone of the Lorraine Formation (Simony, 1964; Mackean, 1968).

7. MARQUETTE STUDY AREA LITHOFACIES ASSOCIATIONS

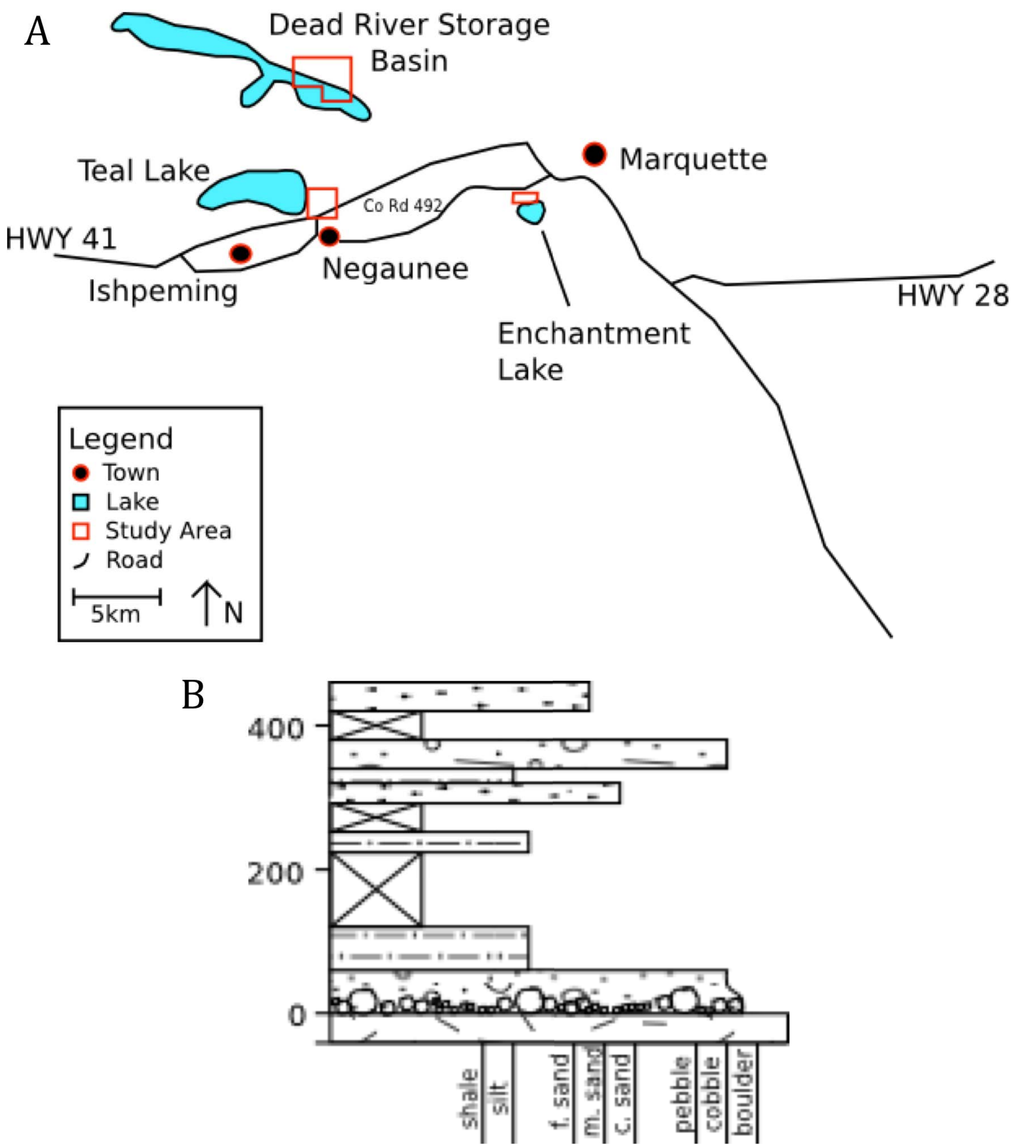


Figure 7.1 A) A map of the Marquette, Michigan study area showing the locations where outcrops were logged to compile data. B) A general stratigraphic column of the rocks that are correlated to the Gowganda Formation (scale is in meters).

There are two glaciogenic formations in the Marquette area of Paleoproterozoic age, the Reany Creek Formation, of the Chocolay Group, and the Enchantment Lake Formation. There is some debate as to whether these formations can be correlated to the same glacial event. Both of these formations stratigraphically overlie Archean basement and both contain diamictite layers (Puffett, 1969) as well as dropstones. However, the Reany Creek formation is bordered by faults and is argued to possibly be Archean in age. Being as these formations are present in such close proximity to each other, and there are no Archean glacial events recorded in the rest of the Canadian Shield, it is reasonable to assume they are one and the same and can ultimately be correlated to the Gowganda Formation (Ojakangas, 1988). In addition, Vallini et al. (2006) constrained the depositional age of the Chocolay Group to 2300-2200Ma using detrital zircons and diagenetic xenotime, correlating it geochemically with the Huronian Supergroup. A map of the Marquette study area with the locations where outcrops were logged to compile data is shown in Figure 7.1A. A general stratigraphic column of the outcrops logged north of the Dead River Basin, Michigan is shown in Figure 7.1B and the lithofacies associations are described in detail in the following chapter.

7.1 Basal Conglomerate Lihofacies Association

The Basal Conglomerate LA is visible in outcrop north of Highway 41 near Teal Lake (Fig. 7.1A). Here, the contact between the matrix-supported conglomerate and the underlying metamorphosed Archean metabasalt is sharp. The matrix of the conglomerate is comprised of a poorly sorted muddy-siltstone and sand-sized grains. The clasts are predominantly quartz in composition and are granule- to cobble-sized, with the largest measuring 12cm in diameter (Fig. 7.2A). The layers of conglomerate range from 23 to 160cm thick and contain approximately 35 to 60%

clasts, varying from matrix- to clast-supported. In one layer of conglomerate, elongated clasts are aligned parallel to strike (Fig. 7.2B). In addition to the conglomeratic layers, one layer 50cm thick, contains very coarse-grained sand to granule-sized clasts that are uniformly distributed throughout the muddy-siltstone. A 6cm thick layer of siltstone is also present as well as two layers, 3.5 and 2.5m thick respectively, of quartz granules with little to no matrix present. The latter two layers contain rounded to subrounded cobbles and pebbles at the base of the layers that die out up section. The contacts between the layers in this LA are all sharp and planar.

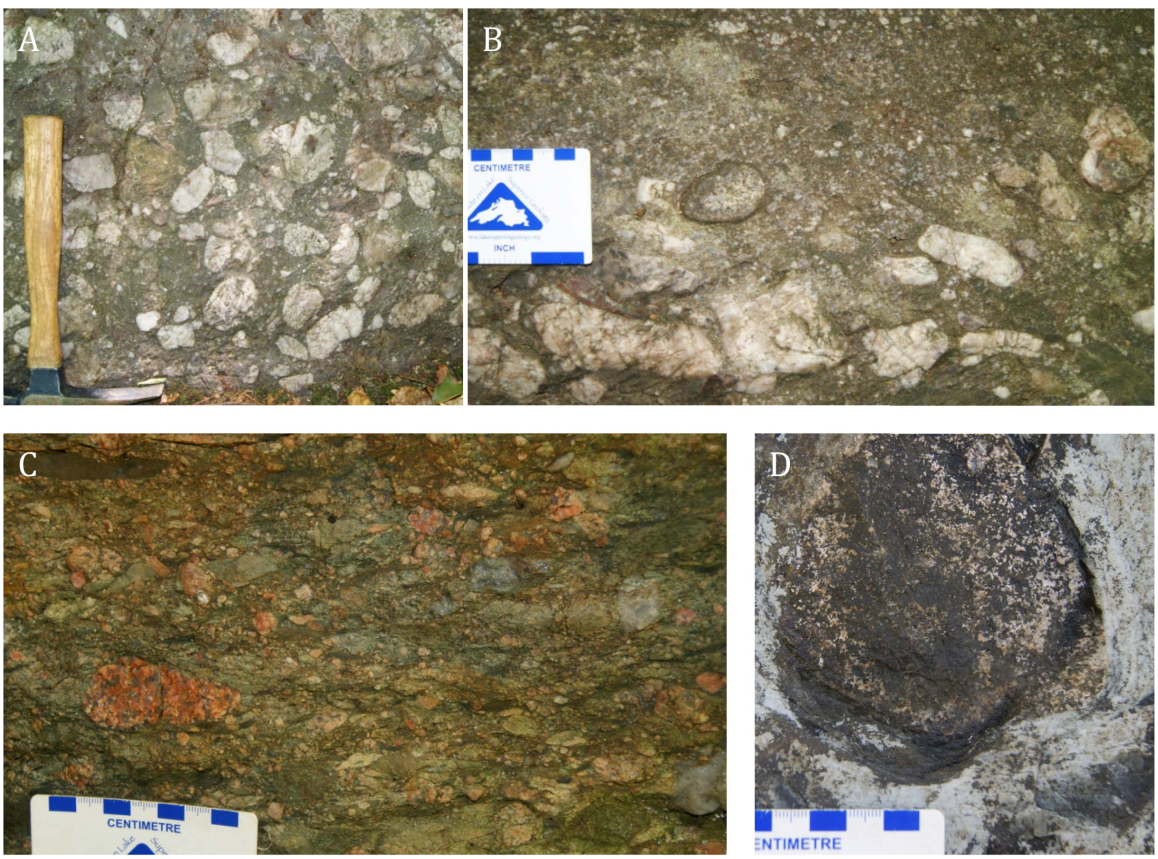


Figure 7.2 A) Basal conglomerate with a matrix of muddy-siltstone and sand and outsized clasts of predominantly quartz near Teal Lake. B) Elongated clasts aligned parallel to strike in one horizon of the conglomerate. C) Basal conglomerate near Enchantment Lake composed of poorly-sorted matrix of siltstone and sand with clasts of granite, quartz and Archean basalts. D) A granitic clast in the Diamictite LA with laminated muddy-siltstone building up around it.

Approximately 18m stratigraphically above the contact with the Archean basalts, there is a sharp drop-off in the outcrop, which likely indicates a lithology change as erosion suddenly increased. This drop-off is followed by 17m of covered forest floor and some small outcrops of thinly laminated muddy-siltstone before the contact with an outcrop of quartzite.

Outcrops near Enchantment Lake are minimal. However, there is another sharp contact present between very poorly sorted, clast-supported conglomerate and the underlying metamorphosed Archean basalts. The conglomerate is composed of a poorly sorted matrix of siltstone and medium to very coarse-grained sand and granules. The subrounded to subangular clasts of granite, quartz and some angular clasts of the underlying Archean basalts comprise approximately 25 to 35% of the outcrop and are very poorly sorted (Fig. 7.2C).

7.2 Diamictite Lithofacies Association

There are three outcrops north of the Dead River Basin that are composed of matrix-supported conglomerate, approximately 40% clasts, with a poorly sorted matrix of siltstone and sandstone. The clasts are subrounded to angular, range in size from granule to cobble with the largest measuring approximately 20cm in diameter. They are composed of granite, quartz and possible metabasalt. The next outcrop follows approximately 12m of cover and is still a matrix-supported conglomerate with approximately 40% clasts. The last outcrop is again located following approximately 15m of cover. This layer, where visible, is 2.5m thick and is composed of a clast-supported conglomerate. The clasts, that compose approximately 70% of this outcrop, are of similar compositions to the previous outcrops. A 5cm thick silty-mudstone layer drapes the clast-supported conglomerate.

The conglomeratic layers are interlayered with thinly laminated muddy-siltstone with parallel laminations 1 to 4mm thick. The muddy-siltstone appears to drape the conglomeratic layers as the clasts protrude up through the siltstone layers with laminations building up around them (Fig. 7.2D). Approximately 18m from the base of the LA lenses of fine- to medium-grained sandstone appear. In some cases, these lenses, which range from 1 to 30cm thick and 4 to 70cm long, are present as teardrop shapes loading into the underlying silty-mud.

These larger sections of parallel laminated muddy-siltstone are similar to the outcrops that overlie the Basal Conglomerate LA north of Enchantment Lake. Where visible, the LA is composed of muddy-siltstone with 1 to 3mm thick laminations. There are two outsized clasts present within the laminated muddy-siltstone. The first measures approximately 17cm in diameter. This subrounded clast is of granitic composition and appears to be compressing the underlying laminations. The second clast, found roughly along strike with the first, measures 15x10cm and is an orangish-pink colour, possibly of rhyolitic composition.

On the north shore of the Dead River Basin, the LA becomes a more complex interbedding of siltstone, sandstone, conglomeratic and diamictite layers shown in two stratigraphic columns in Figure 7.3. Minor shale layers occur within this LA as both laterally continuous layers and lenses that are between 5 and 15 cm thick. They are parallel laminated with sharp but irregular contacts due to loading of overlying conglomerates (Fig. 7.4A) or deposition on an uneven surface. Stringers of isolated pebble-size clasts 5 to 10 cm long are commonly present within the shale beds. Rare ball and pillow structures of sandstone are also present within the shale layers.

The siltstone layers range from 5 to 20cm thick, on average, and generally become more shale-rich up the logged section indicating a slight increase in the mud content. The contacts between the siltstone and the adjacent layers are sharp and their internal structure can be either massive or parallel laminated (Fig. 7.4B). In addition to the well-sorted siltstone layers, there are siltstone layers with coarse grains distributed throughout them. These layers measure 10 to 40cm thick and the isolated coarse grains range in size from coarse sand to small pebbles (Fig 7.4B). This secondary coarse grain population has a uniform grain size giving the overall bed a bimodal size distribution. In some cases, the grains will occur as 5 to 10 cm long, 0.3 cm thick stringers of granules or as 30 cm long stringers of pebbles that are one pebble thick. These stringers are similar in appearance to small lag deposits. Rare granite dropstones are also present in the siltstone, with the largest clasts penetrating the underlying siltstone laminations.

The layers of diamictite range from approximately 10 to 20cm thick and are composed of a well-sorted siltstone matrix with outsized clasts of granule- to pebble-size. Unlike the siltstone with coarse grains lithofacies, these outsized clasts are not uniformly sized, nor are they distributed uniformly throughout the siltstone matrix. The diamictite can be laminated or massive (Fig. 7.4C). Thin layers of mudstone approximately 0.5cm thick are periodically found within the diamictite. These layers have sharp contacts and are parallel laminated.

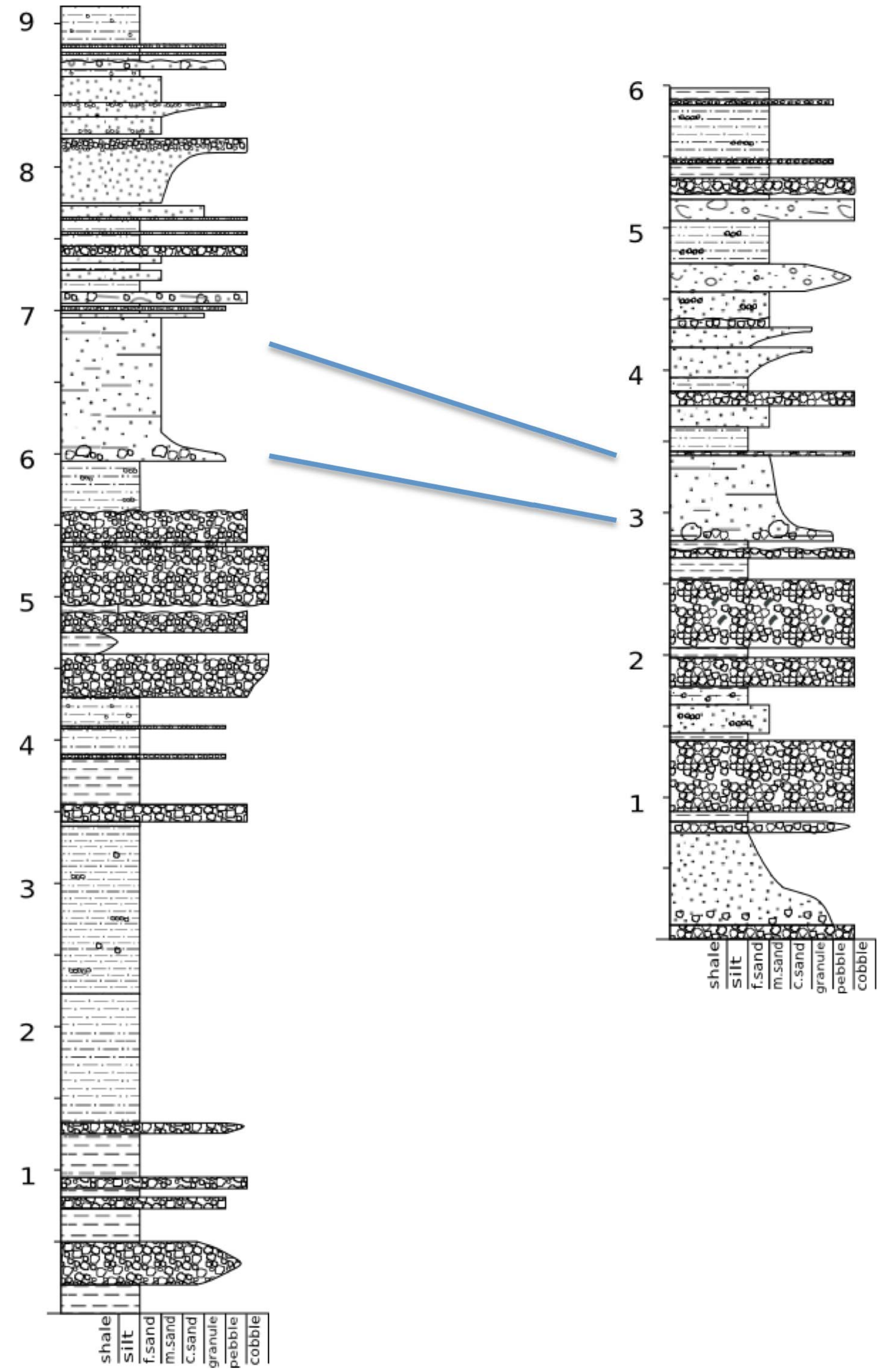


Figure 7.3 A stratigraphic column (scale is in meters) of the complex interbedding of siltstone, sandstone, conglomeratic and diamictite layers that compose the Diamictite LA on the north shore of the Dead River Basin, Michigan. These two outcrops are approximately 10m from eachother and are correlated using a graded sandstone layer that had a boulder lense at the basal contact.

Fine- to coarse-grained sandstone layers are present that measure 10 to 90cm thick and can be massive, parallel laminated, trough cross-stratified or hummocky cross-stratified and may contain reverse grading. In one case, faint antidune stratification is present. The sandstone layers are well-sorted except for isolated granule-sized grains commonly dispersed throughout. The granule-sized grains seem to represent a second population of well-sorted grains despite the fact that they are in matrix support within the sandstone. In some cases, these grains occur as stringers or as lenses, 10 to 20cm long and 0.3 to 1cm thick. Layers of parallel laminated mud, 0.5 to 1cm thick, are found interlayered with the fine-grained sandstone, as well as granite dropstones that range from 4 to 7cm in diameter. The hummocky cross-stratified layers are 5 to 10cm thick and contain a layer of parallel laminated sand at the base with an overlying layer of cross-stratification with low angle truncation surfaces (Fig. 7.5A). The coarse-grained sandstone layers that are present can be laterally continuous or can occur as layers that pinch out laterally and are approximately 40cm long. These pinched out layers are poorly sorted with a large proportion of matrix material present (Fig. 7.5B). In some cases, angular mud rip-ups were present within the thicker coarse-grained sandstone layers. Faint trough cross-stratification is rare and is present in the basal portion of a few thicker sandstone layers.

The pebble conglomerate layers are approximately 10 to 50cm thick and are predominantly clast-supported with a siltstone or mudstone matrix. The clasts are subrounded to subangular and well-sorted with minor occurrences of granules and cobbles. Clasts are mainly granitic in composition but sandstone and mudstone

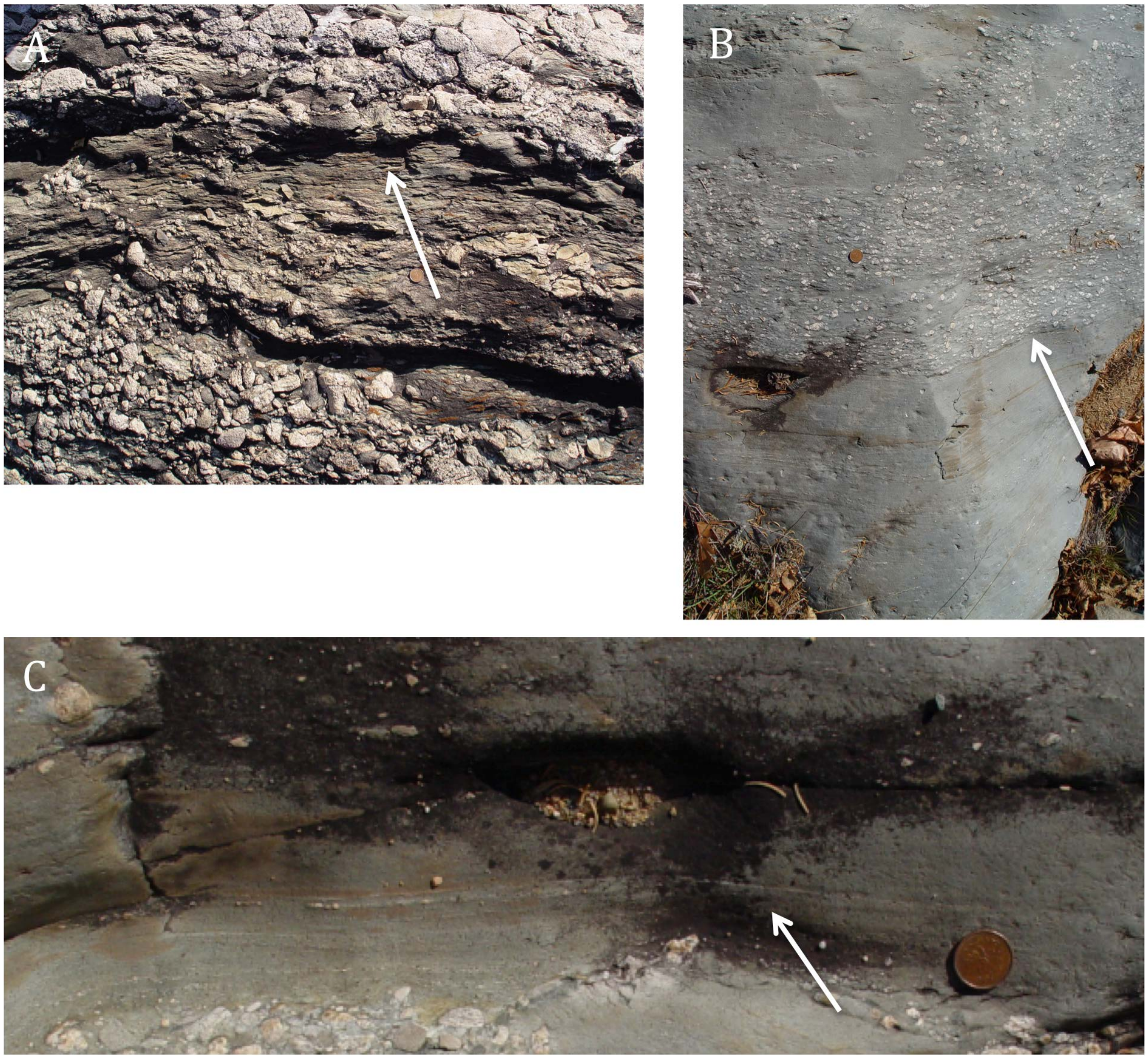


Figure 7.4 A) Shale being loaded by an overlying conglomerate (arrow). B) A sharp contact between siltstone and the overlying siltstone with coarse grains (arrow). Notice the penny roughly in the middle of the outcrop, which is used for scale. C) Diamictite with a matrix of siltstone with coarser grained rainout clasts dispersed throughout. In this case the diamictite changes from laminated at the bottom of the bed (arrow) to massive in the top half of this photo. The diamictite layer is underlain by a clast-supported, pebble conglomerate layer.

clasts are also common. The mudstone clasts are similar in composition to the matrix of the conglomerates and have well defined edges indicating they are intraformational clasts instead of mud injected due to loading (Fig. 7.5C). The conglomerates occur as continuous layers through the two logged sequences as well as lenses that are several meters long. The conglomerates are generally massive with rare reverse grading from small pebbles to cobbles. In many cases, the basal clasts are loading into underlying siltstone layers creating diapirs of fine-grained material, which have been injected into the conglomerate. The sharp contacts are not horizontal and are instead quite irregular making it appear as though the conglomerates have undergone some contortion and possible loading into the underlying mud or silt layers. Rarely, these contacts intersect horizontal laminations of underlying siltstone beds (Fig. 7.5C).

In some cases, lag deposits are present within the diamictite layers. They are composed of granules to small pebbles and are approximately 1 to 2 cm thick. The diamictite layer underlying the lag deposit has the same sized granule and pebble population scattered throughout the matrix. However, the layer overlying the lag deposit is composed of siltstone without outsized clasts. They differ from the siltstone with coarse grains lithofacies as they are thicker, more concentrated beds of granules to small pebbles (Fig. 7.6A).

A distinct sedimentary feature in this LA is a large pile of dropstones that is located near the base of a normal graded sandstone bed (Fig. 7.6B). One boulder in the lense measured 105cm in diameter, while the cobbles ranged from 5 to 20cm. The lens is laterally continuous between the two stratigraphic sections. The laminations of the underlying sediments show evidence of compression (Fig. 7.6C). The overlying layers abut against the dropstones until sedimentation raised the surrounding bottom, burying the dropstone lense.

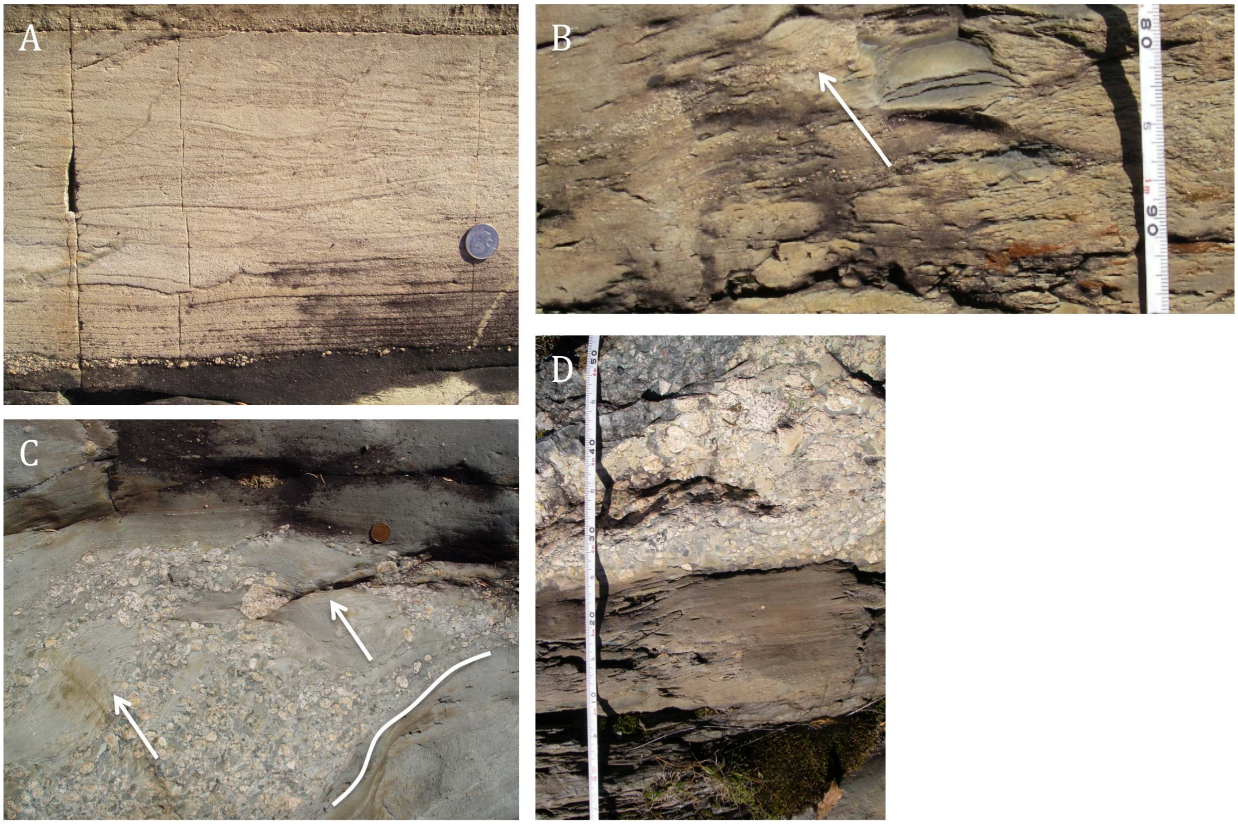


Figure 7.5 A) The hummocky cross-stratified sandstone beds contain a layer of parallel laminated sand at the base with an overlying layer of what appears to be cross-stratification with low-angle truncation surfaces. B) Coarse grained sandstone facies composed of coarse grained sand and granules interbedded with fine grained sandstone. These particular layers are quite thin and pinch out laterally (arrow). C) Shows the pebble conglomerate with subrounded and well sorted granite clasts along with intraformational mud clasts (arrows). The basal contact of the conglomerate is cross cutting a bed of horizontally laminated siltstone (white line). D) Clast-supported pebble conglomerates showing the subrounded clasts and a sharp contact with the underlying siltstone. This photo shows slightly smaller clasts in the basal portion of the layer than in the upper portion. This could be similar to the basal reverse grading seen in the Elliot Lake study area.

Following approximately 50 to 75m of cover, 11m of coarse-grained sandstone that averages roughly 150cm a layer, overlies the previously described outcrop. These coarse sandstone layers are clay-poor and contain pebble-sized balls of sandstone. These balls of sandstone are rounded and are of a similar composition to the rest of the sandstone layer (Fig. 7.6D). These 11m of coarse-grained sandstone are stratigraphically overlain by a gradual contact and another succession of interlayered mudtone, siltstone, sandstone and conglomeratic layers. Granitic dropstones and outsized clasts are present within the siltstone and sandstone layers respectively. Reverse grading is relatively common within the sandstone layers from fine- to medium-grained sandstone at the base of the layer to coarse-grained sandstone or even granules and small pebbles at the top. A few thin, matrix-supported conglomeratic layers of granule- and pebble-sized clasts with minor cobbles in a clay-rich sandstone matrix are present.

Figure 7.6 A) Shows the granule to small pebble conglomerate (arrow), which appears to be a lag deposit due to the fact that the underlying bed contains a similar sized population dispersed throughout. B) The large lense of iceberg dumped material. The overlying sediments are shown here draping overtop of the lense (arrow). For scale, the large boulder is 105 cm in diameter. C) One of the cobbles in the lens is shown here compressing the underlying sediments. D) Rounded balls of sandstone that are of similar composition to the sandstone beds in which they are found.

8. DISCUSSION

8.1 Planar Cross-Stratified Sandstone Lithofacies Association

The Planar Cross-Stratified Sandstone Lithofacies Association (LA) is representative of the Upper Serpent Formation. The LA was likely deposited in an open water, shallow marine setting due to the presence of hummocky cross-stratification interlayered with wavy, flaser and lenticular bedding (Duke et al., 1991; Long and Yip, 2009).

The dominant sedimentary structures associated with open water storm deposits are hummocky cross-stratification, wave ripple cross-lamination and planar or trough cross-stratification (Aigner, 1985). Hummocky cross-stratification was first characterized by Harms et al. (1975) and is defined as isotropic stratification with low-angle erosional bounding surfaces. Within each set, the laminations commonly decrease in dip upwards. These sedimentary structures have been observed in numerous outcrop exposures and are generally accepted to form in sand that is reworked by storm and swell waves in a shallow shelf environment, below the fair-weather wave base, under strong oscillatory flow (Duke et al., 1991; Long and Yip, 2009). Most recently, this stratification has been proposed to develop due to instabilities in combined flows, but there is still a general consensus that it is created under storm conditions (Dodd et al., 2004; Quin, 2011).

Fine-grained sandstone layers, with the small-scale, low-angle truncations indicative of hummocky cross-stratification, are present in the LA and commonly have upper bedding surfaces of symmetrical, bifurcating wave ripples. These ripples were then draped by mud. A progression upsection from hummocky cross-stratification to wave ripples is usually representative of a waning storm event as the flow regime decreases in intensity (Duke et al., 1991). The mud layer indicates the return to fair-weather deposition, as sedimentation is again dominated by suspension settling of the finer-grained sediments (Duke et al., 1991). These processes all indicate deposition occurring on the inner to possibly mid continental shelf.

In addition to the storm deposits, layers of interbedded sandstone and mudstone are common within the LA also supporting a shallow marine environment. Interlayered sandstone and mudstone forming flaser to lenticular bedding can occur in any environment as a result of deposition in fluctuating energy conditions, the sand portion being deposited during the higher flow regime periods, while the mud is deposited during slack water conditions (Weimer et al., 1982). Wavy bedding, defined as interlayered rippled sandstone and mudstone layers (Reineck and Wunderlich, 1968), is the most prevalent form of these types of bedding present in the LA. Layers of flaser bedding, sandstone with mud flasers, and lenticular bedding, mudstone layers with lenses of sandstone, are present in the LA, but sparse. Tidal shelf depositional models of the late Precambrian Jura Quartzite (Anderton, 1976) as well as the late Precambrian Lower Sandfjord Formation (Levell, 1980a) and the Cambrian Eriboll Sandstone Formation (McKie, 1990a,b) are all composed of predominantly cross-stratified sandstone interbedded with sections of interlayered sandstone and mudstone. The finer-grained sediments representing lower-relief surfaces that were blanketed by the mudstone during fair-weather conditions (Levell, 1980b).

Soft-sediment deformation structures such as ball-and-pillows, pseudonodules and sand injectites are common within the LA. A variety of soft-sediment deformation structures have been recognized in shelf deposits around the world resulting from deformation during or soon after deposition as well as during compaction or diagensis (Allen, 1982b). Soft-sediment deformation has been documented in ancient shelf settings of the Rosita Delta, Texas (Edwards, 1981), the Eocene Basin, Spitsbergen (Plink-Bjorklund et al., 2001; Mellere et al., 2002) and the Karoo Basin, South Africa (Wild et al., 2009). Load structures, including pseudonodules and ball-and-pillow structures, as well as water-escape structures like the sand injectites, are formed in situ, due to the liquidization of fine-grained sediments (Lowe, 1975). This indicates, as would be expected in a shallow marine environment, that the sediments had a very high water content at the time of deposition.

In the northern section logged in the Espanola study area, on Iroquois Bay, the sandstones of the Planar Cross-Stratified Sandstone LA were interbedded with layers of carbonate rocks. Carbonate rocks are widely accepted as indicating deposition in warm to temperate subaqueous environments (Bennet et al., 1991) but they have also been documented in the rock record of cold water, interglacial subaqueous environments (James et al., 2005). These rocks most likely represent an interlayering with lithologies similar to the underlying Espanola Formation. Their presence within this LA indicates a gradual transition occurred in a near-shore, shallow marine environment from the underlying carbonate dominated environment into an environment dominated by clastic deposition.

All of the above mentioned characteristics of this LA are consistent with a shallow marine environment with tidal influences and the preservation of storm deposits. Therefore, it is reasonable to assume that the large-scale, low-angle planar stratified layers that are prevalent in this LA, and appear as though they could be beach deposits, are in fact of a shallow marine origin as well. Tidal sandwaves, large-scale bed features common in tide dominated shelf deposits of shallow seas, can produce unidirectional planar cross-stratification and commonly have a decrease in the foreset angle from approximately 25° to 10° in the down current direction (McCave, 1971; Walker, 1984; Bose et al., 1997; Nemeth et al., 2007). The low-angle planar cross-stratification preserved in this LA can be dipping as little as 3° to 5° which is significantly lower than angles of dip discussed in the literature. To account for this difference in dip angle it is possible that the cross-stratification documented in this thesis represents preservation of the sediments at the base of the lee side of widely spaced sandwaves. As the sand grains avalanche down the steep, lee side of the wave, they splay out onto a near horizontal surface between the sandwaves. A flow separation occurs between the sandwaves, creating a zone of lower energy where little to no erosion will occur, similar to Class 4 sandwaves discussed by Allen (1980). Meanwhile, the upper, high-angle portions of the sandwaves are removed by migration of the next up-current sandwave (Fig. 8.1). As a rule of thumb, deposition only occurs when an excess of sediment is introduced into an environment. In the case of the sandwaves, very limited sand input into the system could account for the majority of these large-scale bedforms being removed by erosion.

There are rare examples in the Espanola study area of the higher-dip, upper portions of sand waves being preserved overlying the basal, low-angle counterparts (see Fig 3.4B). This lends support to the model put forth in Figure 8.1.

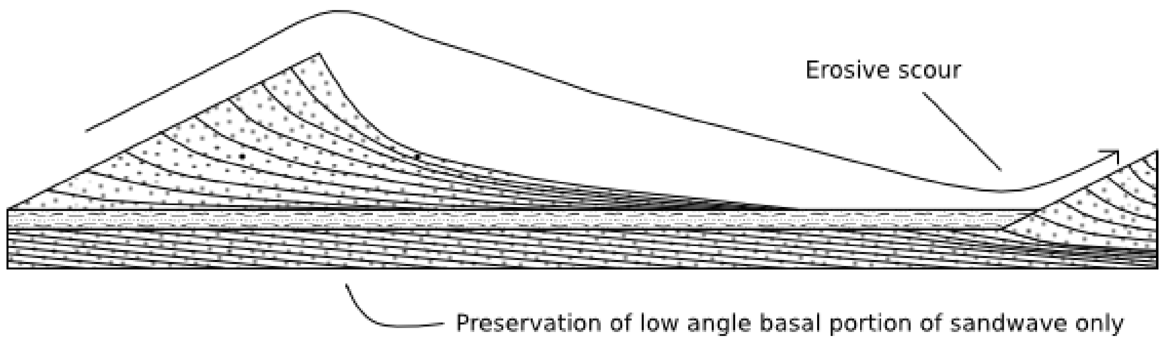


Figure 8.1 A possible mode of deposition and erosion resulting in the preservation of only the low angle basal portion of the sandwaves.

The mud drapes commonly separating the sandy foresets, in particular at the base of the layers, are also indicative of a tide-generated structure (e.g., Houbolt, 1968; Allen, 1982a; Stride, 1982). The strongly asymmetrical cross-stratification of the sandwaves is probably due to a strongly asymmetrical tidal current, likely created by the coupling of the tide with a one-way current, such as a wind-drift off of the continent, or a result of the coriolis effect. The sand foresets were deposited as the dominant tidal current surpassed the threshold necessary to move sand grains while little or no sand was moved during the lower energy tide. During this period of low-energy flow, or more likely during slack water between tidal currents, mud would be deposited from suspension as a drape along the foresets (Allen, 1982a). These mud drapes would be preferentially preserved in the low-angle foresets and between the sandwaves as the flow separation that creates a low-energy zone allows for better preservation of sediments.

Trough cross-stratified sandstones can also be associated with these environments and are created by the periods of nearly symmetrical reversing tidal currents similar to Class 6 sandwaves described by Allen (1980).

Data compiled on the late Precambrian to early Cambrian shallow marine sandstones of northern Norway are often used to describe a facies model of a shallow, current- and storm-dominated sandy marine succession (Banks, 1973a,b; Johnson, 1975, 1977; Johnson et al., 1978). The description of the Planar Cross-Stratified Sandstone LA closely matches the high-energy, current-dominated shelf zone located in the proximal offshore area. A schematic model for the depositional environment of this LA is shown in Figure 8.2A at the end of the discussion section. This facies is typically dominated by tidal currents with variable storm re-working, sandwaves, sand bars and winnowed zones along with a mainly coast-parallel paleocurrent. This could be an explanation for the paleocurrent trend to the west in the Espanola study area which differs from the general north/south trends shown in lower fluvial and deltaic sedimentary successions (Long, 1978; Fralick and Miall, 1989).

It should be noted that the Planar Cross-Stratified Sandstone LA is only present in the Espanola and Elliot Lake study areas. In general, there is inconsistent preservation of the Serpent Formation throughout the Huronian Supergroup. In the northern study areas of Thessalon and Cobalt, where the overlying Gowganda Formation is directly in contact with the Archean basement, it is reasonable to assume that they are representative of sub-aerial regions of non-deposition during Serpent time. At that time, not enough subsidence would have occurred to allow sedimentation of the Serpent Formation to occur in these areas. In the southern study areas of Elliot Lake and Espanola, which are assumed to have been further from the ancient continental margin, preservation is still sparse. In this case, it is hard to determine whether the Serpent has been eroded or rather that deposition merely did not occur, possibly due to an irregular paleotopography, or dominance of the Espanola carbonate system. These interpretations correspond to subaerial to shallow-marine environments proposed by Long (1976) and Young (1981a; 1981b). Long (1976) also interpreted the presence of carbonate layers and lenses within the Serpent Formation to be representative of sabkha deposits.

8.2 Basal Breccia Lithofacies Association

The Basal Breccia Lithofacies Association (LA) is present in certain localities throughout the Cobalt and Kirkland Lake study area. Where present, it marks an unconformity surface between the underlying steeply dipping stratified Archean rocks of the Abitibi Greenstone Belt and the subhorizontal beds of the Coleman Member, Gowganda Formation (Mustard and Donaldson, 1987b). The breccia was documented in the town of Cobalt by Mustand and Donaldson (1987a,b) as well as during the fieldwork conducted for this thesis. It was also documented east of Snare Lake in a geological report of Banting Township and the Western part of Best Township by Smyk et al. (1997). In both locations, the breccia is composed of angular fragments of the underlying Archean granitic and metamorphosed basaltic rocks. The breccia is also present in the drill core obtained from outside the town of Elk Lake. The transition into the basal portion of the diamictite is a gradual one and in some locations the muddy-siltstone matrix appears to be draping over and filling in spaces between clasts (Smyk et al. 1997).

The breccia is interpreted to be the result of subglacial deposition, as the clasts of the underlying rocks are incorporated into the basal diamictite therefore a strong relationship between the substrate erosion and the depositional processes of the diamictite is assumed (Mustard and Donaldson, 1987b). On Nippissing Hill in the town of Cobalt, the breccia is present as irregular shaped patches within the underlying Archean basalts making it appear as though it filled in topographic lows of the Paleoproterozoic paleotopography. Mustard and Donaldson (1987a) interpreted irregular shaped depressions within the Archean rocks to be a result of ice-plucking from the highly jointed bedrock surface. These features, in addition to south-facing steps and stoss-and-lee erosional structures, are thought to have formed beneath a south-moving grounded ice mass (Mustard and Donaldson, 1987b).

At the south end of Lake Temagami, the basal contact of the Gowganda Formation and the underlying Archean basement is visible at the aptly named "Contact Cliff" (Schenk, 1965). The basement surface in this location is polished, continuously striated, well-grooved and pitted and is interpreted to be a result of grounded ice moving over the rocks (Schenk, 1965). The grooves and striae preserved in the basement surface generally trend to the south as well indicating a southward-moving grounded ice mass (Schenk, 1965). Similar features were documented by Rosen (1985) near the towns of Gowganda and Elk Lake.

Further north, the Basal Breccia LA is absent at the contact in the Kenogami Area. This could be the result of inconsistent preservation due to paleotopographic highs and lows.

A similar breccia composed of Archean clasts has been documented in Northern Michigan by Cannon et al. (2008). This breccia also has mudstone draping over the angular clasts and filling in spaces between them, closely resembling the clasts documented by Smyk et al. (1997). In this case, the breccia was believed to have formed as a result of the Sudbury impact event. However, it seems plausible that the breccia in Michigan could also be a result of grounded ice erosive processes and subsequently could represent a second occurrence of a sub-Gowganda breccia.

The Basal Breccia LA, as well as grooves and striae documented at the Archean-Precambrian unconformity, indicate grounded ice was likely present in the Cobalt and Kirkland Lake study area during at least the initial advance of the Gowganda ice sheet (Mustard and Donaldson, 1987b).

8.3 Diamictite Lithofacies Association

The Diamictite Lithofacies Association (LA) is representative of the basal portion of the Gowganda Formation. It is present in each of the five study areas but with different characteristics in each location. For simplicity sake, the discussion of this LA will be done separately for each study area. A schematic model for the depositional environment of this LA is shown in Figure 8.2B at the end of the discussion section.

8.3.1 Marquette Study Area

In the Marquette study area, the presence of compressed laminations within the fine-grained sediments beneath dropstones indicates floating ice, and the clasts forming the boulder lense corroborate that iceberg dumping was occurring in this environmental setting (c.f., Ovenshine, 1970). For icebergs to be present, deposition must have been in an open water setting, not beneath an ice shelf. Hummocky cross-stratification provides further evidence of this depositional environment as it is created in an open water setting by storm activity above the storm wave base.

A lack of striated clasts within the pebble conglomerate, in addition to the fact that it is clast-supported, with subrounded to subangular and well-sorted clasts, indicate hydraulic sorting occurred prior to deposition (Hunter et al., 1996; Cummings and Occhietti, 2001). The contacts between the conglomerate and its adjacent layers are sharp and in one case the conglomerate actually cross-cuts an underlying layer of parallel laminated siltstone. These contacts, as well as the incorporated mudstone clasts, indicate that the conglomerate was introduced by an erosive flow with varying amounts of material included from preexisting layers (e.g., Eyles et al., 2007). Introduction of these coarse-grained beds would have required a high energy flow but considering they are interbedded with finer-grained materials, this high energy flow was likely episodic. Loading of underlying fine-grained sediments created diapirs, indicating that these sediments were fluidized when or shortly after deposition of the conglomerate was occurring. The diapirs contribute to the sharp, but irregular, shape of the conglomerate contacts. Similar diapirs are commonly observed in channels of coarse-grained mass flow deposits (Delaney, 2002). In addition, the lack of imbrication, presence of subrounded clasts and minimal fine-grained content in the massive conglomerates are all indications that they were introduced by slump events as they moved down the face of a subaqueous slope (Postma, 1984). Miall (1983; 1985) described beds similar to these elsewhere in the Gowganda Formation that are clast- to matrix-supported with subrounded to well-rounded, mainly granitic clasts and some rare intraformational clasts of finer-grained lithofacies. In this case, these characteristics along with a lack of imbricated and striated clasts are used to argue that the beds were resedimented, debris flows of glacial debris. In the Marquette study area, mudstone clasts in the conglomeratic layers have contorted reminant laminations that also support this line of evidence.

Siltstone is common throughout the logged sections as both massive and parallel laminated beds. It makes up the matrix of the diamictite as well as the conglomerates. In some locations, it is also interbedded with fine- and coarse-grained sandstone. The fact that the siltstone occurs in conjunction with the majority of the other clast sizes indicates that it is likely the background sediment deposited from suspension settling of subaqueous outwash material. This is similar to Delaney's (2002) description of subaqueous glacial outwash fan deposits that are dominated by beds of sand and silt and cross-cut by channels of coarser-grained materials. Similarly, Veveers et al. (2007) describe the background sedimentation occurring in a subaqueous fan delta system as mainly silt. Both of these cases indicate that it is common for outwash silt to be suspended upon entering a subaqueous environment, and then deposited progressively as the energy of the flow dissipates with increased distance from the sediment source. The predominance of silt is also indicative of a glacial environment as glacial erosion produces large amounts of silt-sized sediment (loess).

There is limited literature that discusses beds like the siltstone with coarse grains documented in this study area although Veveers et al. (2007) mention a similar type of bed where granules are in matrix-support within sandstone on a fan-delta. They attribute the bed to a resedimentation event and this seems a probable explanation in this environment as well. The bed is poorly-sorted due to the presence of the bimodal grain-size population meaning a proximal resedimentation event could have combined two well-sorted layers, one of silt and one of coarse sand. This would account for the uniform size and distribution of the coarser grains throughout the siltstone.

Fine-grained sandstone could be the equivalent to siltstone on areas of a subaqueous fan that are more proximal to the outwash source. Their introduction into the portion of the fan dominated by siltstone would require either a higher energy outwash event or a mass-flow event. Evidence for both cases is present. Weak antidune stratification and parallel laminations within the fine sandstone layers suggests that traction currents were at work during the time of deposition. These beds have sharp contacts and are interbedded with siltstones indicating they represent a period during which a higher energy outflow reached the more distal areas of the fan, which are normally dominated by deposition from suspension. In the cases where the fine-grained sandstone layers are reverse graded to coarse-grained sandstone and the contacts are not as sharp, it suggests the flow may have lost contact with the bottom, thus allowing the initial ramping-up of velocity to be preserved as the resultant coarsening upwards trend.

The coarse-grained sandstone layers represent thin sheets of subaqueous glacial outwash that are of an intermediate intensity compared to the fine-grained sandstone and conglomerate layers. Where they are present as poorly-sorted, lense-shaped beds they are thought to be created by small debris-flows, generated by slope failures on a subaqueous fan (e.g., Mohrig et al., 1998). Although there are not many comparable successions in the literature, this is a plausible explanation as the coarser conglomerates in this LA also show evidence of slumping.

Both the granule to small pebble conglomerates, as well as the thin stringers of coarser grains forming within the fine sandstone layers indicated current re-working was taking place. A loss of finer-grained sediments commonly occurred and effectively concentrated these coarser grains into small lag deposits. An additional current is needed to explain this process because if it were merely the glacial outwash currents at work they would have brought more fine-grained sediments with them. A possible explanation could be geostrophic currents that were being generated in the open water environment. Geostrophic currents are created in the ocean when forces generated by the Coriolis effect equal those generated by the pressure gradients. The resulting flow of water is perpendicular to the isobars and is referred to as geostrophic.

Massive and stratified diamict can form in a range of settings, meaning it is not indicative of any one environment and the accompanying lithofacies should be used to determine the origin (Eyles et al., 2007). In this particular glacial environment, there is a limited amount of diamictite, suggesting that rainout is not the major depositional process occurring and the majority of the sediments were being introduced from a glacial outwash source. Considering the environment as a whole, the diamictite that is present appears to be ice rafted debris and is composed of outsized, mainly granite clasts, within a siltstone matrix. There are some cases of coarse-grained layers that are better sorted and contain less clay, which creates stratification within the diamictite. The stratification indicates that current reworking processes were taking place, not just debris rainout (Eyles and Eyles, 1983a). In addition, thin layers of mudstone approximately 0.5cm thick are periodically present within the diamictite. These layers have sharp contacts and are parallel laminated providing evidence of periods of extremely low energy when only suspension deposition was active.

The thin shale layers present at other stratigraphic levels are also examples of these short periods of slow deposition, likely representing hiatuses in the introduction of glacial outwash.

A subaqueous glacial outwash fan with small slump and debris flow events, as well as additional current re-working, seems to be the most likely environment of deposition for this succession of sediments. Fan deposits of this sort usually have an interbedding of pebble-sized clasts, sands and silts in addition to some clay laminae and dropstones (Lonne, 1995; Delaney, 2002). Intermediate and high intensity currents would have introduced the debris forming the sandstones and conglomerates respectively, depending on the amount of outwash and seasonal fluctuations (Postma, 1984) while suspension settling of silt produced the background sedimentation. The high percentage of siltstone is indicative of a glacial setting as glacial erosion favours silt not mud. The lack of imbrication as well as the lack of fine-grained matrix in the massive conglomerates can be created by slump events as they move down the face of the slope (Postma, 1984). This would explain the evidence of resedimentation events within these coarser-grained beds and their present location, as they are interbedded with the siltstone that is more characteristic of an environment distal to the sediment source. These resedimentation events are also thought to account for the creation of the siltstone with coarse grains lithofacies being as there is little in the literature that describes similar beds. Additional current re-working is responsible for the presence of thin lag deposits throughout the section and could be explained by geostrophic currents. These geostrophic currents are feasible in the open water environment that is indicated by the hummocky cross-stratification and iceberg rainout debris.

8.3.2 Thessalon Study Area

The most distinctive lithofacies present within the Diamictite LA in the study area north of Thessalon are layers of diamicite. Diamictites are defined as lithified mixtures of sand and larger clasts, which are dispersed throughout a matrix that is generally high in clay content (Flint et al., 1960). Deposition of diamictite can be achieved in any environment that produces the characteristically poorly sorted layers (Eyles et al., 1983). For example, diamictite can be deposited subaqueously through rain-out processes of debris-laden basal ice or as subglacial till (Link et al., 1994; Hoffman, 2011). The layers of diamictite in this LA have dropstones, parallel laminations, evidence of current activity, and are found interbedded with sandstone layers that are interpreted as subaqueous debris flows, indicating they were probably produced by the former process.

Outsized clasts are present throughout both the massive and laminated horizons of the diamictite layers in the study area north of Thessalon. When these clasts are present bending or penetrating the layers within the laminated beds of diamictite they are described as dropstones. Dropstones reinforce the argument that these diamictite layers were deposited in a subaqueous environment with an overlying ice source as they are released from the floating ice and are deposited within the soft-sediments of the bottom, compressing the laminations (Thomas and Connell, 1985; Hoffman, 2011). The overlying ice source can be in the form of an ice-shelf or icebergs floating in an open water environment. Ice-rafted debris can also be present in the form of small clots of frozen siltstone (Ovenshine, 1970).

In the study area north of Thessalon, small microscopic siltstone clots similar to those described by Ovenshine (1970) were observed in thin sections from laminated samples of an abandoned quarry face along Highway 129 (Fig. 5.2B). In this outcrop, layers of mud-rich siltstone are interlayered with thin mudstone layers. The contacts between these two layers are generally quite sharp which makes them appear more like varves than turbidites (Strum and Matter, 1978). In addition, the small outsized clasts of silt and sand that are visible in the thicker siltstone layers appear to have the sediments building up around them and are rarely penetrating underlying laminations. This would be more indicative of gradual sedimentation that is associated with varves. Varved sediments are representative of an annual cycle of deposition and consist of a siltstone summer layer and a fine-grained, mudstone winter layer (Ashley, 1975; Zolitschka, 2007). The siltstone layers are composed of sediments that rain out of suspension from overflows and interflows and are carried along the bottom by underflows throughout the summer months (Strum and Matter, 1978). Whereas the mudstone layers are deposited during the winter months when the water is no longer stratified (Strum and Matter, 1978), often under the cover of overlying ice (Lamoureux, 1999). Varves are created by such regular cycles that the thickness and grain-size of the layers can be relatively consistent over hundreds of meters (Ashley, 1975). This consistent thickness is observed in the interlayered siltstone and mudstone in the quarry face north of Thessalon. Granitic dropstones are present compressing laminations within this outcrop as well, indicating definite periods during which an overlying ice source was present (Thomas and Connell, 1985). According to mapping done by the Ontario Geological Survey (Chandler, 1976), the sequence of varve-like deposits is present stratigraphically overlying and underlying large sections of the Diamictite LA. These varve-like deposits are therefore thought to represent deposition during periods of relatively ice-free water with minimal icebergs present.

The layers of diamictite in this LA range from massive beds to beds with well-preserved parallel laminations. Massive diamictite beds can be attributed to high sedimentation rain-out rates originating from an overlying ice shelf. As much as 1m of melting can occur at the base of an ice shelf over the course of a year, contributing large amounts of sediment to the marine floor (Thomas, 1979). Ice shelves limit the water movement and decrease or inhibit the presence of currents allowing for sediments that lack stratification to accumlate (Mackiewicz et al., 1984; Link et al., 1994; Visser, 1994). Some of these thicker layers of massive diamictite were documented in the area north of Thessalon.

In contrast, the presence of siltstone laminations within some horizons of the diamictite layers indicates periods during which under-flow currents or traction currents were present, possibly due to seasonal fluctuations in meltwater or sediment supply (Eyles and Eyles, 1983a; Powell, 1988, 1990). In outcrop on Jobammegeshig Lake, some of the clasts are even aligned parallel to what is assumed to be bedding as well as along faint cross-stratification surfaces. These currents most likely originated at the ice front in the form of subaqueous glacial outwash (Visser, 1994). Small lag deposits within the diamicitite layers also indicate the periodic presence of bottom current activity that sorts and winnows the sediments (Eyles and Eyles, 1983b).

In one outcrop along Highway 129, north of Thessalon there is an abundance of thick sandstone lenses within the diamictite. These thicker sandstone lenses are generally massive, medium-grained sandstone with a homogeneous texture. The massive texture could be primary resulting from rapid deposition of the sediments (Rust, 1968) or secondary due to fluidization shortly after deposition (LeBlanc and Eriksson, 1979). The basal contact of the sandstone layers is erosive as there are rip-ups of the diamictite matrix within the sandstone layers. Loading structures are common along these contacts as well, with the sinking of the sandstone into the underlying fine-grained diamicitite matrix also indicating rapid deposition (Rust and Romanelli, 1975). These characteristics are commonly associated with rapid channelized deposition of the sandstone in environments with abundant subaqueous glacial outwash (Rust and Romanelli, 1975; LeBlanc and Eriksson, 1979).

The sandstone is also present within the diamictite matrix as irregular shaped patches or lenses that are concave-up like loading structures or sometimes as very angular blocks or whispy patches. These are likely created by the breakup or loading of sediment-starved, thin sand layers or lenses that were deposited on the water-saturated, muddy-silts that composed the subaqueous diamictite matrix similar to those discussed by Miall (1983) in the Cobalt region.

Dropstones are also present, compressing laminations within the sandstone layers. The continued presence of the dropstones indicates icebergs were present for the duration of the deposition of the Diamictite LA. In some cases they are arranged as isolated stringers or concentrated layers of clasts. It is not possible to describe these layers as lag deposits being as there are no outsized clasts distributed throughout the rest of the sandstone. Therefore, as previously mentioned, the sandstone are likely erosively introduced channelized debris flows that occurred at the same time as ice rain-out.

In general, the Diamictite LA in the study area north of Thessalon shows evidence of sandy mass-flows but not the conglomeratic mass-flows that were documented in the Elliot Lake and Espanola study areas indicating it could be further from an outwash source. There is also no evidence of wave or storm reworking of the sediments. There is however evidence of a continued presence of an overlying ice source in the form of thick diamictite rain-out units and dropstones in the finer-grained sediments, as well as abundant evidence of bottom hugging currents in the form of laminated diamictite layers.

8.3.3 Elliot Lake Study Area

Drill core was used to aid with the interpretation of the depositional environments of the Diamictite LA in the Elliot Lake study area. Miall (1985) conducted a similar investigation of drill core from the area and determined abundant sandy and gravelly sediment gravity flows that likely occurred on a continental shelf or slope. He noted that the drill core could not be correlated to nearby outcrop indicating lateral facies variability or internal disconformities in the lower Gowganda Formation.

Clast-supported conglomerate layers are commonly interbedded with the diamictite layers in this study area. These layers are composed predominantly of rounded to subrounded clasts that range in size from graunules to boulders. The rounded nature of the clasts indicates some sort of abrasion, likely fluvial, has occurred prior to their introduction into this environment (Hunter et al., 1996; Cummings and Occhietti, 2001). These layers have sharp contacts with the adjacent sandstone and diamictite layers and can either be present in continuous layers or lenses. These contacts, along with the inclusions of angular rip-ups of the diamictite matrix within the conglomeratic layers indicate they were introduced as channelized erosive flows, likely in the form of sediment gravity flows, cutting down into the underlying sediments (Miall, 1985). High-density flows, as described by Lowe (1982), are composed of coarse-grained sand and clasts from granule- to boulder-sized along with some finer sediments, similar to the conglomeratic layers in the Diamictite LA.

The conglomeratic layers can be massive, normally graded from cobbles to small pebbles and granules and in some cases, reverse grading is visible in the basal portion of the layers. Excellent examples of the basal reverse grading are visible in outcrop along Highway 108 in the Elliot Lake study area. Non-cohesive, high-density turbidite flows are the most plausible explanation for the grading that can be present in the conglomeratic layers (Lowe, 1982). Non-cohesive flows are supported by collisions between the grains that create dispersive pressure as a result of shearing (Bagnold, 1954). Dispersive pressures are responsible for supporting the sediments in grain-flows. These grain-flow processes can operate within high-density turbidity currents creating inverse grading in the basal portion of the turbidite deposits as the smaller clasts are kinetically sieved to the bottom of the layers (Middleton, 1970; Lowe, 1982). The inversely graded basal portion of the layers is only preserved when deposition is rapid. Initially, the turbidity current will winnow out the finer-grained sediments, which will be deposited as normal grading downslope as sedimentation from suspension begins to dominate (Hampton, 1972; Walker, 1975). The layer then begins to slowly "freeze" due to a decrease in velocity. As the center of the flow "freezes" it forms a rigid plug, which will erosively scour the underlying sediments (Lowe, 1982). These characteristics can be observed in the majority of the conglomeratic layers of the Gowganda formation (Miall, 1983).

Where these clast-rich layers were observed in drill core in the Elliot Lake study area, it was not possible to correlate them between the different drill holes. Miall (1983), encountered similar problems when logging core of the Gowganda Formation and attributed it to the fact that these debris flows were of limited widths or were constrained due to irregular paelotopography. Similarly, Mutti and Ricci Lucchi (1972) described sandy-conglomeratic turbidite facies on submarine fans as commonly channelized.

The most distinctive lithofacies present within the Diamictite LA are layers of diamicite. As previously mentioned, the deposition of diamictite can be achieved in any environment that produces the characteristically poorly sorted layers (Eyles et al., 1983). The layers of diamictite in this study area have dropstones within them and are found interbedded with the conglomeratic layers that are interpreted as subaqueous debris-flows, indicating they have a subaqueous origin. The conglomerate layers and sandstone layers that are interlayered with the diamictite indicates that resedimentation of the rain-out debris by gravity flow is occurring. These two processes often occur simultaneously in subaqueous environments (Eyles and Eyles, 1983a; Visser, 1983).

The layers of diamictite in this LA can range from massive beds to beds with well-preserved parallel laminations. As previously described in the study area north of Thessalon, massive diamictite beds can be attributed to high rain-out sedimentation rates. Minor layers of massive diamictite were documented in the Elliot Lake study area.

In contrast, the presence of laminations within some horizons of the diamictite layers indicates periods during which under-flow currents or traction currents are present, possibly due to seasonal fluctuations in meltwater or sediment supply (Powell, 1988, 1990; Eyles and Eyles, 1983b). These currents most likely originated at the ice front in the form of subaqueous glacial outwash (Visser, 1994). Small lag deposits and sandstone layers within the diamicitite layers also indicate the periodic presence of bottom current activity that sorted and winnowed the sediments.

In outcrop along Highway 108, north of Elliot Lake there is an interfingering of the diamictite layers and thick sand lenses. These thicker sand lenses occur in conjunction with the conglomeratic layers, that as previously mentioned are interpreted to be high-density turbidity currents. Therefore it can be assumed that the sandstones are produced by similar currents depositing finer-grained sediments (Lowe, 1982). In the Elliot Lake study area, the sandstone layers and lenses are generally well-sorted, medium- to coarse-grained sandstone with some rare pockets of very coarse-grained sand and granule- to cobble-sized outsized clasts. These sandstone layers are often massive with rare parallel laminations throughout or wave ripple laminations present on the upper bedding surfaces. Rip-ups of the siltstone matrix from underlying diamictite layers are often present in the basal portion of the sandstone layers. Le Blanc and Eriksson (1979) described similar erosively based, massive sandstone lenses and layers in a glacially fed deltaic sequence and attributed them to rapidly deposited sediments. The presence of rare wave ripples does however indicate that deposition occurred in water that was shallow enough for periodic reworking of the bottom sediments by wave action. The presence of wave action indicates these sediments were at least at times deposited in an open water setting and not beneath an ice shelf.

The sandstone is also present within the diamictite matrix as irregular shaped patches or lenses that are concave-up similar to loading structures or are sometimes very angular chunks or whispy patches. These are likely created by the breakup or loading of sediment-starved, thin sandstone layers or lenses that were deposited on the water-saturated, muddy-siltstone that formed the subaqueous diamictite matrix (Miall, 1983).

Lenses or irregular shaped clast-rich patches are commonly present within the diamictites layers. These clast-rich zones are composed of granule- to cobble-sized clasts and have a sandier matrix than the surrounding diamictite matrix. These zones could be a result of periods during which current activity in the water mass was increased. This would result in the removal of clay and fine silt as the sediments rained down to the ocean floor, ultimately creating a sandier more pebble-rich diamictite. Another possibility is that these clast-rich patches could be small iceberg dumps however, they are not in the shape of mounds which is usually expected in this case.

An interesting observation in the drill core used for this thesis, was that the basal, approximately 42m of the Diamictite LA in the Elliot Lake study area, consisted of a high percentage of white-coloured granitic outsized clasts. This was followed by a gradual increase in the number of pink-coloured clasts. One possible explanation for this observation could be a change in the source rock of the outsized clasts. Alternatively, the gradual change in colour could be due to an increase in oxidation. This could ultimately be linked to the gradual increase in oxygen that would have been occurring in the atmosphere during the time leading up to the 'great oxidation event'. The development of an oxygenated atmosphere is thought have occurred right after the Gowganda glaciation (c.f., Hilburn et al., 2005; Sekine, 2011). However, oxidation changing the colour of the granite is not likely as it is not evident in systems operating today.

Abundant resedimentation of glacial outwash sediments has occurred in the Elliot Lake study area. An inability to correlate layers of conglomerate and sandstone between drill core indicates that the majority of the resedimentation of the coarser-grained sediments in the area was channelized (Miall, 1985). The preservation of laminations within some of the diamictite layers as well as rare wave ripples in sandstone layers indicates these sediments were deposited at least periodically in an open water environment that was shallow enough for sediment reworking to occur. The presence of dropstones compressing some of these laminations indicates that deposition from an overlying ice source, likely icebergs, was occurring. All of these characteristics are consistent with the continental shelf or slope depositional environment proposed by Miall (1985).

8.3.4 Espanola Study Area

In the Espanola study area, the presence of compressed laminations within the fine-grained sediments beneath both dropstones indicates that ice-rafted debris was being introduced into this environment (c.f., Ovenshine, 1970). For ice-rafted deposition to occur a marine environment is inferred for the diamictite LA with an overlying ice source such as a shelf or icebergs. The presence of stringers, laminations and debris flows in the lower portion of the LA indicates current reworking and resedimentation processes were operating most likely in an open water environment. Upsection, the presence of hummocky cross-stratification, which is generated in an open water environment with storm activity, above the storm wave base, indicates a definite open water environment likely on the shallow mid- to inner-continental shelf.

Matrix- to clast-supported conglomeratic layers, composed of a sandstone matrix and clasts from granule- to boulder-sized, are commonly interbedded with the diamictite layers in the Espanola study area. These layers are composed predominantly of rounded to subrounded clasts that range in size from graunules to boulders. As previously mentioned, this indicates some sort of fluvial action has caused the rounding likely prior to their introduction into this environment (Hunter et al., 1996; Cummings and Occhietti, 2001). These layers have sharp contacts with the adjacent sandstone and diamictite layers and can either be present in lenses or continuous layers. These contacts, along with the inclusions of angular rip-ups of the diamictite matrix within the conglomeratic layers indicate they are introduced as channelized erosive flows (e.g., Eyles et al. 2007), likely in the form of sediment gravity flows, cutting down into the underlying sediments similar to those described by Miall (1985) in the Elliot Lake area. High-density flows, as described by Lowe (1982), are composed of coarse-grained sand and clasts from granule- to boulder-sized along with some finer sediment, which are similar to these conglomeratic layers.

The conglomeratic layers can be massive, normally graded from cobbles to small pebbles and granules and in some cases, reverse grading is visible in the basal portion of the layers such as in outcrop on McGregor Bay. Non-cohesive, high-density turbidite flows just as in the Elliot Lake study area are the most plausible explanation for the grading that can be present in the conglomeratic layers (Lowe, 1982). Injections of the underlying fine-grained sediments into the conglomeratic layers indicate that these sediments were fluidized during or shortly after deposition of the conglomerate. The injections contribute to the sharp, but irregular, shape of the conglomerate contacts and are commonly observed in channels of coarse-grained mass-flow deposits (Delaney, 2002). In one outcrop on McGregor Bay, a lense of conglomerate had a flat bottom and a curved upper surface, taking on a mound-shape. This could be a possible dump structure that can be created when large amounts of debris are deposited by the break-up or over-turning of an iceberg (Thomas and Connell, 1985).

The diamictite layers that are interbedded with these conglomerates average approximately 7.8m in thickness. In the lower portion of the LA these diamictite layers have minimal laminations and dropstones, outsized clasts that are compressing underlying laminations. Rare clast-poor horizons within the diamictite layers showed evidence of preserved laminations. This could indicate that the majority of the diamictite layers, at least in the lower portion of the LA, were in fact fine-grained, cohesive debris flows (c.f., Johnson, 1970; Lowe, 1982; Nemec and Steel, 1984). This could account for the lack of laminations in the majority of the diamictite layers.

In outcrop on McGregor Bay, there is an interfingering of the diamictite layers with thick sand lenses. These thicker sand lenses occur in conjunction with the conglomeratic layers, that as previously mentioned are interpreted to be high-density turbidity currents therefore it could be assumed that the sandstones are deposited by a similar process (Lowe, 1982). These turbidity currents would have been composed of a higher sand content with some rare granules and small pebbles.

Outsized clasts are present throughout the diamictite and sandstone layers and can also be arranged as stringers one clast thick. Eyles and Eyles (1983b) credited the formation of more sorted layers similar to stringers to be due to traction current reworking.

Overall there is likely a gradual transition into the Diamictite LA from the underlying Planar Cross-stratified Sandstone LA where it is present. In the Espanola area in particular, planar cross-stratified sandstone layers similar to those in the underlying LA are interlayered with the initial diamictite and clast-rich conglomeratic layers. The contacts between the layers are sharp, indicating erosive, high-energy flows introduced the conglomerate and sandstone layers as the environment slowly changed to one dominated by diamicitite deposition. The presence of cross-stratification in the sandstone layers, similar to those in the Planar Cross-Stratified Sandstone LA, indicates the continued presence of tidal deposits into the basal portion of the Diamictite LA.

The upper bedding plane of one of these sandstone layers is marked by a sharp V-shaped structure in the sand infilled by clasts of the overlying conglomeratic layer (Fig. 3.9C). At first glance, the V-shape closely resembles that of an ice wedge. However, the structure is in sediments previously interpreted to be subaqueous and ice wedges usually develop under subaerial permafrost conditions (Black, 1976). In addition, this is the only structure of its kind observed in any of the study areas and according to Black (1976) single wedges are often suspect. Burbidge et al. (1988) described V-shaped water escape structures in sandy beds that closely resemble ice-wedge casts in subaqueous outwash near St. Lazare, Quebec, which seems like a more plausible explanation in this particular case. Some of the clasts filling in the wedge are aligned perpendicular to bedding. As the water flows upwards, at a relatively high velocity, it is capable of entraining sediment by fluidization a process in which sediment grains can be supported by the drag of upward moving water (Lowe and

LoPiccolo, 1974). This could account for the alignment perpendicular to bedding of some of the clasts within the V-shaped structure.

Near the top of the Diamictite LA in the Espanola area, sandstone layers become more common. These upper sandstone layers are generally more mud-rich and can be massive, parallel laminated, cross-stratified or ripple-drift cross-laminated and in some cases possibly hummocky cross-stratified. Basal contacts of the sandstone layers are sharp, while the upper contacts are more gradual. Rip-ups of the siltstone matrix that are commonly present within the basal portion of the sandstone layers in addition to the sharp contacts, indicate these sandstone layers are likely episodic, erosive, sandy debris flows introduced into the predominantly muddy-siltstone dominated environment.

Ripple-drift cross lamination was originally described by Jopling and Walker (1968) as superimposed undulating ripple laminae that show a slight lateral displacement in each successive lamination. These sinusoidal cross-laminations are preserved when deposition from suspension is high as the entire ripple structure is preserved before being altered by traction currents. Ripple-drift cross-lamination has been described in depositional environments where underflows of sediment-laden subaqueous glacial outwash are present (Jopling and Walker, 1968; Rust and Romanelli, 1975). In outcrop on McGregor Bay, in the Espanola study area, layers of ripple-drift cross-lamination were documented in close association to possible hummocky cross-stratification. This association indicates that these sediments were likely deposited in an open water, shallow marine environment, below fair-weather wave base, where storm activity was preserved.

In the upper portion of the Diamictite LA, the interbedding of diamictite layers with clast-supported conglomeratic layers and sandstone layers is likely representative of subaqueous glacial outwash fan deposits similar to those documented in the Marquette study area. These fans form where sub-glacial streams exit into the standing water of the ocean and as the velocity of the water decreases suddenly, the sediments being transported are deposited. Over time, these subaqueous deposits accumulate in the shape of a fan (Cheel and Rust, 1982; Powell, 1988; 1990; Lonne, 1995; Delaney, 2002). Gravels, composed of larger clasts, are deposited proximal to the outwash source whereas sands and silts are often thrown up into suspension and deposited in areas distal to the source as the velocity of these outwash currents wanes (Hoffman, 2011). Resedimentation of the glacial outwash sediments commonly occurs by debris flows and turbidity currents as oversteepening or destabilization of the fan or a re-advance of the ice front can occur (Kurtz and Anderson, 1979; Delaney, 2002; Hoffman, 2011). The normal and inverse grading present in the conglomeratic layers are indicative of these mass-flow events as they are produced by the action of dispersive pressure. In addition, the ripple drift and ripple cross-stratification documented in the sandstone layers, indicate that traction current resedimentation is also prevalent in these deposits. The diamictite layers that are interlayered with the debris-flow sediments are likely from interchannel areas (Cheel and Rust, 1982). Possible hummocky cross-stratification indicates a probable open water depositional environment with some storm reworking, while the dropstones that persist throughout the upper portion of the LA indicate the presence of an overlying ice source.

8.3.5 <u>Cobalt Study Area</u>

In the northern study area near Cobalt, the Diamictite LA is composed of a complex interbedding of diamictite, poorly sorted sandy matrix-supported conglomerate, sandstone and laminated siltstone layers. There is less evidence of laminations preserved within the diamictite layers, the majority of which are massive diamictite. This indicates the environment of deposition in the more northern regions may have been occurring beneath an ice shelf, which decreases the movement of the water and dampens current activity (Robin, 1979; Jacobs et al., 1979). Initially, deposition could also have been beneath grounded ice suggested by the underlying breccia. Conglomerate and sandstone layers are present interlayered with the diamictite, which are interpreted by Miall (1983) to be resedimentation events that have occurred on subaqueous outwash fans. Rain-out deposition and resedimentation of these deposits often occur simultaneously (Eyles and Eyles, 1983a; Visser, 1983). Dropstones are widely preserved compressing laminations within the laminated siltstone sections of the LA attesting to the presence of overlying ice (Thomas and Connell, 1985).

In the drill core, the diamictite layers of the Cobalt study area are relatively thick ranging from 1 to 28m. The matrix is commonly massive, but there are horizons of faintly laminated siltstone indicating some water movement, typical of depositional environments beneath ice shelves (Robin, 1979; Jacobs et al., 1979; Mackiewicz et al., 1984; Link et al., 1994; Visser, 1994). In addition to the laminated siltstone, thin layers or lenses of fine- to medium-grained sandstone are also present. These are most likely sediment starved sandstone layers that have undergone soft-sediment deformation in the water-saturated, fine-grained sediments of the diamictite matrix (Miall, 1983).

Outsized clasts interpreted as dropstones are present throughout both the massive and laminated horizons of the diamictite layers. The presence of dropstones again reinforces the argument that these sediments were deposited in a subaqueous environment with an overlying ice source as they are released from the floating ice and are deposited within the soft-sediments of the bottom, compressing the laminations (Thomas and Connell, 1985; Hoffman, 2011). The overlying ice source can be in the form of an ice-shelf or icebergs floating in an open water environment.

Laminated siltstone sections compose a large portion of the Diamictite LA in the Cobalt study area. For the most part, these laminated successions are scattered between the diamictite sections. They are composed of alternating layers of siltstone and silty-mudstone or mudstone usually parallel laminated but with localized sections of wave and current ripple cross-laminations. They are interpreted by Miall (1983) to be deposited by suspension settling with episodic weak traction currents. Thin layers and lenses of fine- to coarse-grained sandstone are present interbedded with the siltstone. These layers are often loaded into the underlying silt or mud layers indicating deposition on water saturated fine-grained sediments, which is to be expected in a subaqueous environment. Planar cross-laminations are common within the sandstone layers. In environments that are proximal to a sediment source, high-energy, sediment-ladened outwash events can generate episodic underflows that deposit cross-laminated sandstone layers (Ashley, 1975; Strum and Matter, 1978; Aigner and Reineck, 1982; Lamb et al., 2008). Some layers grading from fine-grained sand or silt to mud were also present interlayered with the siltstone. Turbulent underflows, often generated by flood events or extremely energetic outwash, can deposit their sediment loads as complete or incomplete Bouma sequences resembling these fine-grained turbidites (Nelson, 1982; Prior and Bornhold, 1989; Reading and Collinson, 1996).

Dropstones are common within the laminated siltstone sections of the Diamictite LA throughout the entirety of the Cobalt study area. They were documented in drill core from the town of Elk Lake, in outcrop near the town of Cobalt and Lake Temagami as well as from the northern limit of the study area by Miall (1983). This widespread presence of dropstones indicates large-scale ice-rafting of sediments that persisted for the duration of the deposition of the Coleman Member. The presence of rare balls of sandstone, most likely sand clots, within the fine-grained layers also attest to the presence of ice-rafted debris (Ovenshine, 1970).

Zones of brecciated, contorted clasts with preserved internal laminations of siltstone and mudstone are present throughout the sections of laminated siltstone. Similar brecciated fragments of interlayered siltstone and sandstone present on Lake Temagami were described by Simony (1964) and interpreted to be characteristic of a slump event. Slumping is a common process amidst fine-grained sediments in subaqueous, sloped environments (Lee et al., 1996; Eyles and Lagoe, 1998; Stoker et al., 1999, Nitsche et al., 2000, McHugh et al., 2002). Another possible slumped area, composed of contorted chunks of fine-grained sandstone within a siltstone matrix, is present on the eastern side of the southwest arm of Lake Temagami. Granule- to cobble-sized granite clasts are also present within these outcrops.

The sandstone layers present within the Cobalt study area were generally moderate- to well-sorted with rare granules or pebbles throughout. These layers were commonly graded from coarse- to medium- or fine-grained sandstone. The basal contacts were sharp with frequent rip-ups of the underlying finer-grained sediments present. These characteristics indicate the sandstones were introduced by erosive flows that cut down into the underlying fine-grained diamictite or laminated sections. This is consistent with Miall's (1983) description of similar sandstone layers in the Gowganda Formation to the north of Elk Lake. These sandstone layers were interpreted to be deposited by high-viscosity sediment gravity flows (Miall, 1983) similar to those described in subaqueous outwash fans by Rust and Romanelli (1975) and Rust (1977). There was a cyclicity to the sandstone layers that were interbedded with the diamictite layers and in general there was an upward fining of the grainsize and a decrease in bed thickness. Miall (1983) interpreted this to be the possible result of glacial retreat phases when less sediment would be supplied to the environment. There are minor parallel laminations, likely upper flow regime traction deposits, and cross-laminations present within the sandstone layers. These characteristics coincide with Miall's (1983) interpretation of the sandstone layers to the north indicating that at least episodic traction currents, possibly from turbidity currents, existed during the depositional process.

The layers of conglomerate present in the Cobalt study area are commonly poorly-sorted, matrix-supported conglomerate with a higher sand content than conglomeratic layers discussed elsewhere. In this study area, medium- to coarse-grained sand comprises the matrix of the conglomerates. There are however, some layers of conglomerate in clast-support that were documented during field work for this thesis, near the town of Matachewan. Where present, the contacts between the poorly sorted matrix-supported conglomerate and the laminated siltstone and diamictite are sharp with common rip-ups in the basal portion of the layers. The conglomeratic layers often grade into overlying sandstone layers and can therefore be interpreted as high-density sediment gravity flows (c.f., Lowe, 1982), similar to those described in the Elliot Lake and Espanola study areas (Miall, 1983; 1985). As previously mentioned, the presence of reverse grading in the basal portion of some of these conglomerate layers is a typical characteristic of non-cohesive, high-density turbidite flows that are described by Lowe (1982) and are only preserved when deposition is rapid. As previously discussed, these characteristics are present in the majority of the conglomeratic layers of the Gowganda formation (Miall, 1983; 1985).

Miall (1983) hypothesized that an irregular basin floor could create locations where ice rises stabilize a possible overlying ice shelf. This could account for the widespread presence of dropstones in the Cobalt study area. This could also create smaller isolated areas of grounded ice, which could account for the localized patches of the Basal Breccia LA. An irregular basin floor would allow for numerous sources of sediment gravity flows, which could be the reason for such a complex interbedding of diamictite, sandstones, conglomerates and laminated siltstones in the Cobalt study area.

8.3.6 Second Succession of the Diamictite Lithofacies Association

In the Elliot Lake and Espanola study areas, a second succession of the Diamictite LA is present stratigraphically overlying a section of the Interlayered Siltstone and Fine-Grained Sandstone LA and the Heterogeneous Sandstone LA. It is represented by Figure 8.2E at the end of the discussion section. The second succession of the Diamictite LA is much thinner than the first (Figs. 3.2A,C; 4.1B; 6.1B). This second succession of the LA tends to have a higher sand content within the siltstone matrix of the diamictite layers. In the Espanola study area, outcrops on McGregor Bay have sandstone layers with small climbing dunes and possible hummocky cross-stratification interbedded with the diamictite layers. On Iroquois Bay, the second succession is present as large lenses of diamictite-like sediments within thick layers of sandstone (Fig. 3.17D). Near Elliot Lake, the second succession of the Diamictite LA was interpreted from data collected in drill core as well as Ontario Geological Survey maps of the area. It is similar to the previous Diamictite LA with a slightly sandier matrix.

It is hypothesized that the ice disappeared from the Cobalt study area at a later time than in the southern study areas making stratigraphic correlations difficult (Junilla and Young, 1995). In drill core from the Cobalt study area, a possible second succession of the Diamictite LA was very similar to the first succession of the LA with a muddy-siltstone matrix and outsized granitic clasts.

In the Thessalon area, the second succession of the Diamictite LA was not visible or not present. While in the Marquette study area, limited rock exposures make it difficult to determine if there were two occurrences of the Diamictite LA. The outcrop logged on the north shore of the Dead River Basin is the most continuous exposure and it appears to be composed of only one thin Diamictite LA.

8.4 Interlayered Siltstone and Fine-Grained Sandstone Lithofacies Association

The Interlayered Siltstone and Fine-Grained Sandstone Lithofacies Association (LA) is comprised predominantly of thinly laminated layers of silty-mudstone, muddy-siltstone and very fine- to fine-grained sandstone which show evidence of current and wave activity. The preservation of small-scale hummocky cross-stratification structures in these fine-grained sediments, with their characteristic low-angle truncations, indicates the presence of storm activity (Harms et al., 1975). Therefore, an environment with protracted periods of quiet water that allowed deposition from suspension to predominate, but also shallow enough for periodic wave-reworking of the sediment to occur is proposed, such as the inner to middle continental shelf (c.f., Escutia, 2003; Williams et al., 2008). More specifically, these sediments resemble those of a prodelta sequence (Reading and Collinson, 1996; Lamb et al., 2008) and were interpreted as such by Junnila and Young (1995). A schematic model for the depositional environment of this LA is shown in Figure 8.2C at the end of the discussion section. Downslope resedimentation is common in prodeltas and the presence of the Slump LA (to be explained in the following section) indicates mass movement of the fine-grained laminated sediments as would be expected in such an environment (Eyles and Lagoe, 1998; Galloway, 1998; Stoker et al., 1999; Nitsche et al., 2000). The relative absence of dropstones indicates a lack of ice-rafting.

As previously discussed, the presence of hummocky cross-stratification indicates deposition in an open water environment where storm action has reworked bottom sediments (Dodd et al., 2004; Quin, 2011). The preservation of these small-scale, low-angle truncations within the fine-grained sediments of this lithofacies association supports the inner to middle continental shelf, between fair-weather and storm wave base, as a probable depositional environment (Pattison and Hoffman, 2008). The hummocky cross-stratification is interbedded with thin layers of siltstone that either have a sharp upper contact or are graded to a more clay-rich top. These small rhythmic layers are likely the result of fair-weather deposition below the fair-weather wave base whereas the hummocky cross-stratification is the result of particularly intense storm events whose oscillating effects were capable of propagating deeper than usual. In some cases, the interbedded sandstone layers have wave ripple cross-laminations, sedimentary structures that are also commonly associated with storm-dominated processes (Aigner, 1985). These sandstone layers were introduced by traction currents and are interpreted to be storm generated turbidity currents that were capable of eroding and resuspending sand deposits from near-shore environments (Morton, 1981; Nelson, 1982; Soegaard and Eriksson, 1985; Tyler and Woodcock, 1987; Sneddon and Nummedal, 1991; Horikawa and Ito, 2009) or highly concentrated river discharge events (Lamb et al., 2008). In general, the thickness and number of sandstone layers tend to gradually increase upsection in the LA over approximately 80 to 100m. This upwards thickening and coarsening sequence was particularly evident in the Espanola study area where continuous outcrop was visible, but it was also documented in the study areas of Elliot Lake and north of Thessalon. In addition, the appearance higher in the section, of wavy to lenticular bedding as well as minor flaser bedding indicates an upwards coarsening and shallowing trend. The isostatic rebound that occurs during glacial retreat and/or the aggradation of sediments that is common under such circumstances could be responsible for a progressively shallower continental shelf allowing for the delivery of more sand and increased reworking by coastal currents (Boulton, 1990; Januszczak and Eyles, 2001).

In general, the layers of parallel laminated siltstone are most common within this LA and are interbedded with layers of silty-mudstone. The contacts between these layers can be sharp or graded. These fine-grained sediments are likely deposited from suspension representing the background sedimentation style in the deeper, quiet waters of a prodelta environment (Junnila and Young, 1995). Transportation of fine-grained sediments is common as an overflow in deltaic settings. As the current energy wanes, the sediments will be dropped from suspension to the ocean floor, often in the prodelta (Elliott, 1978; Dott, 1963). These fine-grained layers appear to go through coarsening and thickening cycles that could result from the sediment source switching locations for example, deltaic channel migration. The silty-mudstone layers signify extremely low-energy periods during which little to no current activity was present. The rhythmic interbedding of the siltstone and silty-mudstone layers visible in the Espanola study area (Fig. 3.12B) could suggest a cold climate influence with siltstone and mudstone representing seasonal variations in deposition (Gustavson, 1975). The siltstones would be from higher energy summer outwash while the muddy-siltstones would be generated during winter deposition. In contrast to these possibly cyclic deposits, when the contacts between the siltstone and the mudstone are graded they represent discrete events of deposition generated by turbidity currents. The term turbidite is often misused and should be used solely to refer to the deposits of turbidity currents (Shanmugam, 2002). Turbidites are composed of a normal graded bed that represents a single depositional event in which a progressive decrease in flow has led to coarse-grained sediments being deposited first followed by fine-grained sediments (Shanmugam, 2002).

As previously mentioned, the sandstone layers have wave ripple cross-laminations preserved within them. However, these layers can also be parallel laminated or current ripple cross-laminated. In a deltaic setting, deposition from suspension is prevalent accounting for the parallel laminations that are commonly present (Coleman and Prior, 1982). In environments that are proximal to a sediment source, high-energy, sediment-ladened outwash events will generate episodic underflows that are responsible for the cross-laminated sandstone layers preserved within this LA (Ashley, 1975; Strum and Matter, 1978; Aigner and Reineck, 1982; Lamb et al., 2008).

The sandstone layers are also commonly wave reworked due to the presence of symmetrical ripples on the upper bedding plane. Wave reworking is often attributed to storm-dominated processes and would place the environment of deposition above the storm wave base (Aigner, 1985). Turbulent underflows, often generated by flood events or extremely energetic outwash, can deposit their sediment loads as complete or incomplete Bouma sequences (Nelson, 1982; Prior and Bornhold, 1989; Reading and Collinson, 1996). Turbidity currents are commonly generated in continental margin environments and can flow over distances of a few tens of kilometers to hundreds of kilometers accounting for widespread, laterally continuous layers (Galloway, 1998; Stow et al., 1996; Armitage et al., 2010).

Load structures are commonly observed within glacial meltwash deposits (Ashley, 1975; Strum and Matter, 1978; Smith and Ashley, 1985; Yevserov, 2007). This would account for the frequent loading of sandstone into underlying siltstone layers generating pseudonodules or "teardrop" shapes. These loading structures commonly have remnant ripple laminations preserved within them indicating they were introduced by bottom hugging underflows before sinking into the underlying water-rich sediments of the marine bottom.

In addition to the load structures previously discussed, soft-sediment deformation in the form of slumping is quite common amid the finer-grained sediments in subaqueous, sloped environments (Lee et al., 1996; Eyles and Lagoe, 1998; Stoker et al., 1999, Nitsche et al., 2000, McHugh et al., 2002). According to Coleman (1981), nearly half of the sediment present in the Mississippi river delta is involved in some sort of mass movement following deposition. High rates of sedimentation, as well as repeated stress in the form of seismic shock, possibly from isostatic rebound, or storm and wave action could be responsible for the close association of the Interlayered Siltstone and Fine-Grained Sandstone LA with the Slump LA (to be discussed in the following section). Small layers composed of brecciated and contorted clasts with remnant layering preserved within them, similar to the large-scale Slump LA, are common throughout this LA (Stow et al., 1996).

Flaser, wavy and lenticular bedding are discussed in many papers as sedimentary structures that are characteristic to the distal bar portion of a delta system (Coleman and Prior, 1982). These types of bedding appear upsection in the LA in the Espanola study area, in the area north of Thessalon and are quite prevalent throughout the entire Elliot Lake study area LA. The distal bar is the portion of the delta that slopes offshore to the prodelta (Reading and Collinson, 1996). In the case of the Espanola study area, the interbedding of the prodelta fine-grained sediments with the flaser, wavy and lenticular layers of the distal bar indicates a transitional zone created by what was likely a prograding delta. The predominance of these types of bedding in the Elliot Lake area indicates the environment was dominated by distal bar sedimentation. Delta front and distal bar sands can also be introduced into the prodelta area by slump events, which accounts for the chaotically bedded sandstone portion of the Slump LA (Reading and Collinson, 1996).

In the Cobalt study area, the portion of the Gowganda Formation that corresponds to the Interlayered Siltstone and Fine-Grained Sandstone LA is historically named the Firstbrook Member. It is composed of brownish-purple coloured interlayered siltstone, fine-grained sandstone and mudstone layers that range from 0.2 to 6.0cm thick. Apart from the difference in colour, it is essentially the same as the LA in the other study areas. Rainbird and Donaldson (1988) interpreted the Firstbrook Member to be a coarsening-upwards sequence deposited by a braid delta. The repetition of the prodelta section of laminated siltstones, mudstones and interbedded sandstones that was documented in the Espanola and Elliot Lake study areas is not present in the Cobalt study area. The reason for this is not clear although Junnila and Young (1995) attribute it to a later melt back of the glacier in the Cobalt area. Precise stratigraphic correlations between the Cobalt study area and the more southern study areas have not been made but it is hypothesized that the prodelta sequence preserved in the Cobalt area would be correlated with the upper prodelta sequences in the more southern study areas (Junnila and Young, 1995).

A small outcrop of similarly coloured purple siltstone was visible in the study area north of Thessalon. Abundant wave ripples, some herringbone cross-stratification and what appears to be faint hummocky cross-stratification, indicate storm and tidal reworking of these fine-grained sediments. A slump event is also preserved. This lithofacies association is located stratigraphically above the green-grey coloured siltstone of the first Interlayered Siltstone and Fine-Grained Sandstone LA and the Heterogeneous Sandstone LA. This stratigraphic position indicates it can be correlated to the second succession of siltstone in the Elliot Lake and Espanola study areas as well. The preservation of small-scale hummocky cross-stratification structures in these fine-grained sediments is again indicative of the presence of storm activity (Harms et al., 1975). The abundance of wave ripple cross-laminations is also evidence of storm activity in the depositional environment (Allen, 1984; Aigner, 1985). The directional bimodality implied by the herringbone cross-stratifications was described by De Raaf and Boersma (1971) as a diagnostic feature in tidally reworked deposits. Herringbone cross-stratification has been interpreted to indicate tidal activity in a number of sedimentary successions (e.g., Fruit and Elmore, 1988; Alam, 1993; Greb and Archer, 1995; Singh and Singh, 1995; Wignall et al., 1996; Sakurai et al., 2005).

The lack of ice-rafted debris indicates an end to the glacial period in the region when no floating ice was present at the surface of the ocean. A study conducted by

Young and Nesbitt (1999) used a chemical index of alteration (CIA) to compare paleoclimates of the different portions of the Gowganda Formation. The higher the CIA value, the higher the percentage of sediment supplied by chemical weathering. The CIA values of both the diamictite layers and the laminated siltstones of the Gowganda supported large amounts of mechanical weathering, which would be expected in environments dominated by the deposition of glacially eroded sediments. The laminated siltstones however, had slightly higher CIA values than the diamictites which, along with the lack of dropstones or outsized clasts, likely correlates to a lack of sea ice and a period during which the glacier was retreating.

Variations of the Interlayered Siltstone and Fine-Grained Sandstone LA are present in each of the study areas except for Marquette. In the southern sections of the Espanola study area, the LA is located stratigraphically above the Diamicite LA and the transition between the two is gradual with a progressive appearance of bedding as well as a gradual decrease in the number of outsized clasts. In the northern region of the Espanola study area, there are two successions of this LA. The first appearance was found stratigraphically above the Diamictite LA just as in the southern sections. The second appearance however, was located stratigraphically above the Slump LA and Heterogeneous Sandstone LA (to be discussed in the following section). In the Elliot Lake study area, this LA is located stratigraphically above each of the sections of the Diamictite LA with gradual transitions between them. In this area, there is far more wavy and flaser bedding. This could indicate that the outcrops in this area are more representative of the distal bar than the prodelta area itself. These second successions of the LA are shown in a schematic model in Figure 8.2F at the end of the discussion section. In the study area north of Thessalon, the LA again overlies the Diamictite LA. The contact is not visible but it is thought to be gradual. Stratigraphic columns of glaciated continental shelf environments compiled by Edwards (1984) and Visser (1991) show a transition to laminated fine-grained sediments nearing the end of glacial periods. Deposition is no longer dominated by glacial rain-out processes and the shelf becomes progressively starved of sediment as the glacier retreats (Boulton, 1990).

8.5 Slump Lithofacies Association

Soft sediment deformation, for example loading and slumping, is quite common in subaqueous environments. Small slump features are common within the previously described Interlayered Siltstone and Fine-Grained Sandstone LA. The Slump LA itself, shown in Figure 8.2D, is a thick section of large, rounded blocks of undisturbed interbedded mudstones, siltstones and sandstones of the Interlayered Siltstone and Fine-Grained Sandstone LA. Similar internally undisturbed blocks were in a deltaic collapse described by Nemec et al. (1988) and slump structures in general are commonly described in environments fed by glacial sediment (e.g., Ashley, 1975; Strum and Matter, 1978; Le Blanc Smith and Eriksson, 1979; Visser et al., 1984; Smith and Ashley, 1985; Eyles and Lagoe, 1998; Nitsche et al., 2000; Winsemann et al., 2004). In some areas, the layer is predominantly composed of a contorted fine-grained sandstone and slightly more clay-rich fine sandstone. Areas like this are attributed to the fact that the mass of moving material is commonly unconsolidated and undergoes complex internal deformation (Stow et al., 1996). Large-scale mass movements are often attributed to the destabilizing effects of the high pore fluid content that is common in rapidly deposited sediments, such as in a deltaic environment fed by glacial erosion (Rust and Romanelli, 1975) coupled with a source of seismic shock possibly due to isostatic rebound (Stow et al., 1996; Callot et al., 2009; Mosher and Campbell, 2011). Storm activity may also act to destabilize sediments resulting in possible slumping (Lee et al., 1996).

In the Espanola study area, the large-scale Slump LA is present in both of the southern sections that were logged but is missing in the northern section. The northern section does however, have a cyclic repetition of the Interlayered Siltstone and Fine-Grained Sandstone LA and the Heterogeneous Sandstone LA (to be discussed in the following section). Being as this cyclic repetition is not present in the southern region, it is reasonable to assume that the upper of these successions correlates with the Slump LA. This would also account for the chaotically bedded sandstone component of the Slump LA and would indicate that probable sandy, distal-bar sediments are slumping into the deeper, prodelta environment. Thick sections of highly contorted siltstone and sandstone are also present in the study area north of Thessalon indicating soft sediment deformation in the form of slumping was likely a common event amidst the fine-grained sediments of the Gowganda Formation.

8.6 Heterogeneous Sandstone Lithofacies Association

The Heterogeneous Sandstone LA is present in between successions of the Interlayered Siltstone and Sandstone LA in the Espanola, Elliot Lake and Thessalon study areas (Fig. 8.2D) as well as stratigraphically underlying the sands of the Lorraine

Formation. The layers of mudstone or silty-mudstone separating the sandstone layers are generally thicker in the Heterogeneous Sandstone LA than in the Quartz-Rich Sandstone LA. However, the second succession of this LA, which stratigraphically precedes the Quartz-Rich Sandstone LA truly is a transitional LA into the Lorraine Formation as the mudstone layers gradually decrease in number and thickness upsection.

A siliciclastic inner- to mid-continental shelf is proposed as the depositional environment for this LA being as it is present sandwiched either between two successions of the underlying Interlayered Siltstone and Sandstone LA or stratigraphically underlying the Quartz-Rich Sandstone LA. The Interlayered Siltstone and Sandstone LA is considered a prodelta, deposited below fair-weather wave base but above storm wave base, due to the predominance of siltstone and the presence of hummocky cross-stratification. Whereas the Quartz-Rich Sandstone LA (to be discussed in the following section) was deposited in a shallow, sand dominated inner-shelf environment with common large-scale tidally generated structures. That would place the depositional environment of the Heterogeneous Sandstone LA somewhere between the two. The adjacent environments, coupled with the predominance of sandstone layers and lenticular bedding in this LA bears a strong resemblance to the distal bar and lower distributary mouth bar environments described by Coleman and Prior (1982) in the Mississippi Delta.

The presence of hummocky cross-stratification in the south eastern section of the Espanola study area further supports the argument that deposition occurred in a shallow shelf environment where the strong oscillatory flows of storm and swell waves reworked the sand (Duke et al., 1991; Long and Yip, 2009). In addition, the upper bedding planes of the sandstone layers, whether parallel laminated, massive or cross-stratified were commonly reworked by wave or current action. The wave and wave-current reworking is likely also evidence of storm activity (Allen, 1984; Aigner, 1985), whereas the current reworking could be due to particularly energetic bottom-hugging currents.

A sequence of repeating B-C-E turbidites were also documented in the south eastern section logged in the Espanola study area with parallel laminated sands overlain by cross-laminated sands and then a mud top (c.f., Bouma, 1962). These turbidites have erosive bottom contacts and evidence of traction currents indicating they were introduced by high-energy, sediment-laden, bottom-hugging currents. Turbidites with the Bouma sequence B through E record a deceleration in the current that originally carried the sediments (Walker, 1965; Komar, 1985). Storm generated beds in transitional areas commonly display waning flow depositional sequences (Aigner and Reineck, 1982). In addition, the close association with the storm-generated hummocky cross-stratified sandstones indicates that these layers could also be generated by storm events (Nelson, 1982; Jiang et al., 1990; Pattison and Hoffman, 2008; Horikawa and Ito, 2009) or they could have been due to extremely high outwash during flooding events (Strum and Matter, 1978; Lamb et al., 2008), possibly deposited in a subaqueous channel eminating from the river mouth.

Sandstone layers with linguoid and lunate ripple lamination are very common in the northern section of the Espanola study area (Fig 3.15B). Upsection, there is a gradual transition from ripples into larger sedimentary structures such as sandwaves and dunes indicated by the presence of planar and trough cross-stratified sandstone respectively. The predominance of cross-lamination and cross-stratification is common in shelf environments and indicates that a large portion of sediment transport in this LA occurred as bed-load (Ashley, 1990). This transition from smaller-scale to larger-scale structures is consistent with the shallowing upwards trend that is expected between the deeper shelf environment of the Interlayered Siltstone and Sandstone LA and the shallower environment of the Quartz-rich Sandstone LA. This trend is mimicked by the thickness of the sandstone layers, which increase upsection.

The thicker sandstone layers of the LA are commonly interlayered with lenticular-bedded layers. Lenticular bedding is the mud-dominated form of interlayered sandstone and mudstone that is generally associated with the fluctuating energy conditions. Rare layers of wavy and flaser bedding are also present but the predominance of lenticular bedding indicates the high energy conditions that deposited the sandstone layers were interrupted by periods with little to no current or wave activity. Deposition during these times would be from suspension due to the presence of mud- and silt-sized grains. The lenses of sand present within the mudstone layers do have remnant cross-laminations in them indicating these were possibly deposited by lower energy, bottom-hugging currents that were starved of sediment by the time they reached the shelf environment. These energy fluctuations are thought to be associated with storm and flood events where large amounts of sediment are delivered to the distal bar. As the flood energy decreases and conditions return to normal, the sediment is reworked by wave generated currents (Wright and Coleman, 1974; Coleman et al., 1974).

Abundant clay drapes, accentuating the lamination or cross-stratification throughout the sandstones of this LA also differentiates it from the Quartz-Rich Sandstone LA of the Lorraine Formation. Although they are present in the basal Lorrain they are not as common. The mud layer indicates the return to fair-weather deposition, as the deposition is again dominated by suspension settling of the finer-grained sediments. The fact that these drapes are so abundant in this LA indicates more frequent slack-water conditions, which would be expected in a depositional environment that is deeper on the shelf than the shallow, sand dominated inner-shelf of the basal Lorraine Formation.

In the northern section logged in the Espanola study area, granule- to small pebble-sized outsized clasts are present in the upper portion of the first succession of the Heterogeneous Sandstone LA. These outsized clasts are present stratigraphically below the second succession of the Diamictite LA. The presence of outsized clasts in the otherwise well-sorted sandstone layers, as well as the presence of a second succession of the Diamictite LA, indicates a second, short-lived glacial period with floating ice, likely in the form of icebergs.

In the southern sections of the Espanola study area, the Heterogeneous Sandstone LA has a sharp contact with the underlying Slump LA. In addition, the second occurrence of the Interlayered Siltstone and Sandstone LA is not present. It is thought that this is due to the fact that this finer-grained LA is subject to frequent slump events.

In general, the Heterogeneous Sandstone LA is not as well exposed in the Elliot Lake and Thessalon study areas. The outcrops that have been grouped into this LA were done so because of the ripple reworked upper bedding surfaces that were draped by thick mudstone layers.

8.7 Quartz-Rich Sandstone Lithofacies Association

The Quartz-Rich Sandstone LA comprises the basal portion of the Lorraine Formation. This LA is present in all the study areas except for Marquette. It is composed of predominantly quartz- and feldspar-rich sandstone with evidence of tidal influences in the form of common planar and trough cross-stratification, herringbone cross-stratification, minor flaser bedding and mud drapes commonly accentuating the cross-stratification present in the sandstone. Due to the presence of tidally generated sedimentary structures, a sand-dominated shallow continental shelf is a likely environment of deposition for this LA. A schematic model for the depositional environment of this LA is shown in Figure 8.2G at the end of the discussion section. This interpretation coincides with a number of characteristics outlined by Johnson and Baldwin (1996) to describe shelf sandstones including: high textural maturity, a lack of mudstone, significant lateral extent (hundreds of kilometers), common cross-bedding, evidence of current reversals and low-relief erosional surfaces often marked by coarser-grained clays or silt/mud drapes (Levell, 1980b). A similar interpretation of the depositional environment by Rice (1991) states that the Lorraine Formation "inherited a shallow, siliciclastic shelf depositional setting from the Gowganda Formation".

In the Espanola study area, herringbone cross-stratification is present within the sandstones of the Quartz-Rich Sandstone LA. Similar cross-stratification was documented by Rice (1991) in Cobalt. Directional bimodality in cross-stratification was described by De Raaf and Boersma (1971) as a diagnostic feature in intertidal as well as subtidal deposits. Since then, herringbone cross-stratification, with its strong bimodality, has been interpreted to indicate tidal activity in a number of sedimentary successions (Fruit and Elmore, 1988; Alam, 1993; Greb and Archer, 1995; Singh and Singh, 1995; Wignall et al., 1996; Sakurai et al., 2005). Bi-directional paleocurrents obtained from the cross-stratification indicates tidal directions to be in the NE and SW directions (Fig. 3.18B). The presence of minor flaser bedding in the Elliot Lake study area, is also indicative of deposition in an environment with fluctuating energy levels.

Cross-stratified sandstone, either planar or trough, is generated in subaqueous sand dominated environments by sandwaves and dunes respectively (Ashley, 1990). This is one of the most common ancient lithofacies generated by tidal currents in subtidal settings (e.g., Narayan, 1971; Anderton, 1976; Nio, 1976; Levell, 1980b; Allen and Homewood, 1984; Teyssen, 1984; Richards, 1986; Kreisa et al., 1986; Surlyk and Noe-Nygaard, 1991; Long and Yip, 2009; Rahman et al., 2009). Mud drapes accentuating these cross-sets (Figs. 4.9B and 5.8D) are also considered to be indicative of tidal deposits and are thought to be common in offshore tidal shelf deposits (e.g., Houbolt, 1968; Allen, 1982a; Stride, 1982). As previously mentioned in the Planar Cross-Stratified Sandstone LA, the cross-stratification is due to periods during which a strongly asymmetrical tide likely dominated. This situation could be created by the coupling of the tide with a one-way current, such as a wind-drift off of the continent. The sand foresets were deposited by the dominant tidal current while the mud was deposited during the period of low-energy flow (Allen, 1982a). Paleocurrents measured from the cross-stratified sandstones in the Cobalt study area indicate sediment transport was from north to south (Card et al., 1973). In the Espanola area, the general paleocurrent trend is from the northeast to the southwest (Fig. 3.18B). In the Elliot Lake study area, though data is minimal and should not be considered a good representation, one of the trends does correspond with the northeast data from the Espanola study area (Fig. 4.9D). Again in the Thessalon study area there is minimal data, but the trends do show a north to northeast paleocurrent (Fig. 5.9B).

The stringers of granule- to small pebble-sized clasts of quartz and feldspar, which are common in the study area north of Thessalon, closely resemble the description of thin erosive surfaces that are generated in tidal shelf deposits given by Anderton (1976) and Levell (1980b). These surfaces are thought to mark bounding surfaces between sandstone layers and are attributed to winnowing effects of tidal currents.

Soft sediment deformation, in the form of small slumps, which have been preserved in the sandstone layers of the LA have been documented by Card et al. (1973) and Donaldson and Munro (1982). As previously mentioned, soft sediment deformation can be attributed to the destabilizing effects of the high pore fluid content that is common in rapidly deposited subaqueous sediments (Rust and Romanelli, 1975).

A gradual transition from underlying Gowganda Formation into the Lorraine Formation is visible, particularly in the Espanola study area, due to interbedded sandstone and mudstone layers at the base of the Lorraine. A similar succession is documented in Ontario Geological Survey reports from the Cobalt study area (Card et al., 1973; McIlwaine, 1970; 1978) as well as in the Elliot Lake study area and the area north of Thessalon. This general progression upwards from laminated siltstone to interlayered siltstone and sandstone to coarser sandstone is similar to the stratigraphic succession representing a progradation of a delta on the continental shelf.

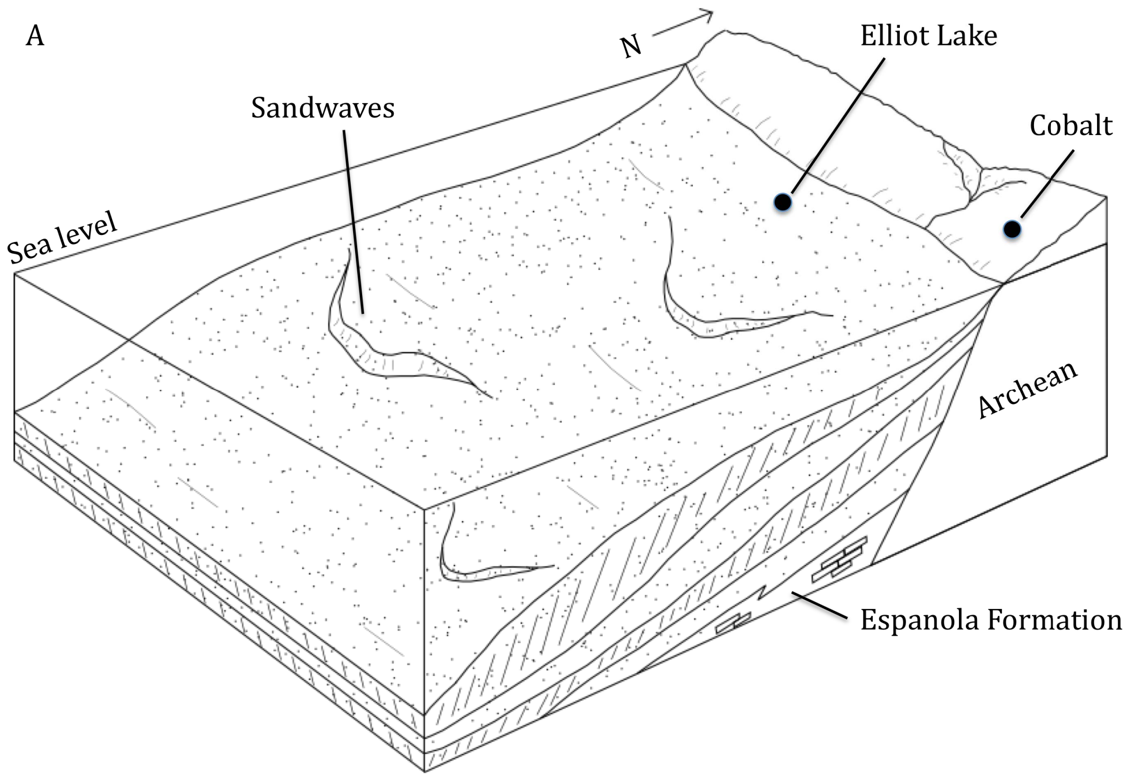
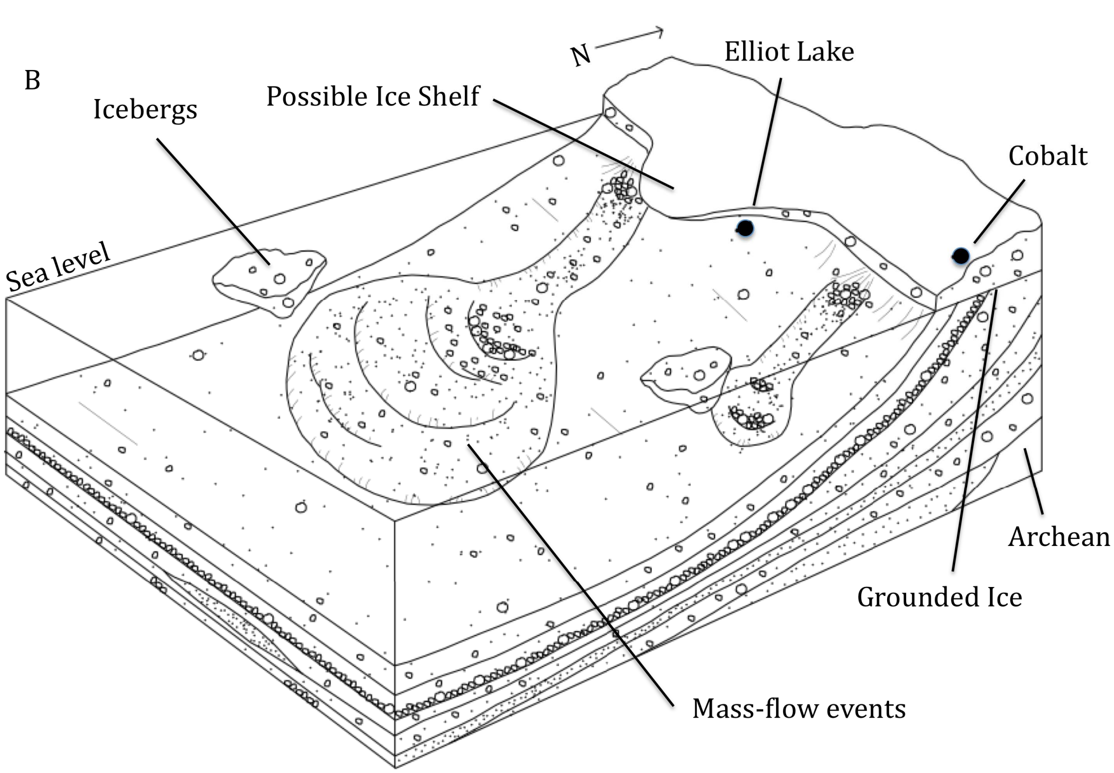
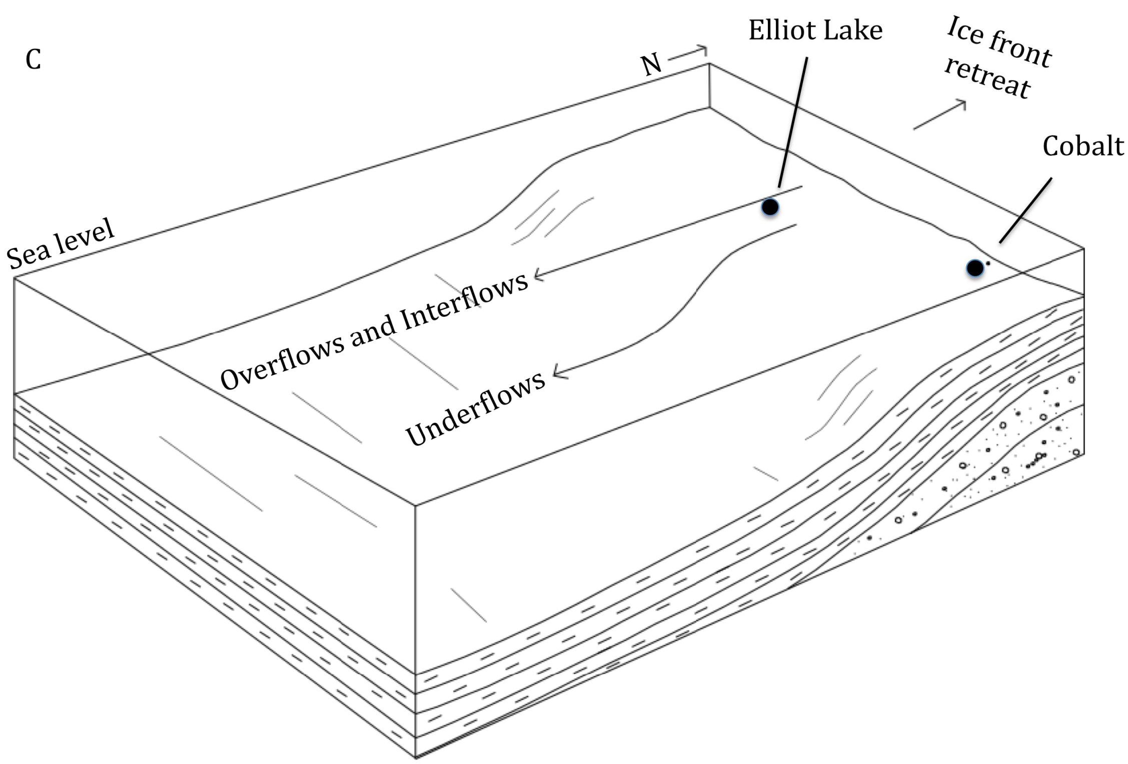
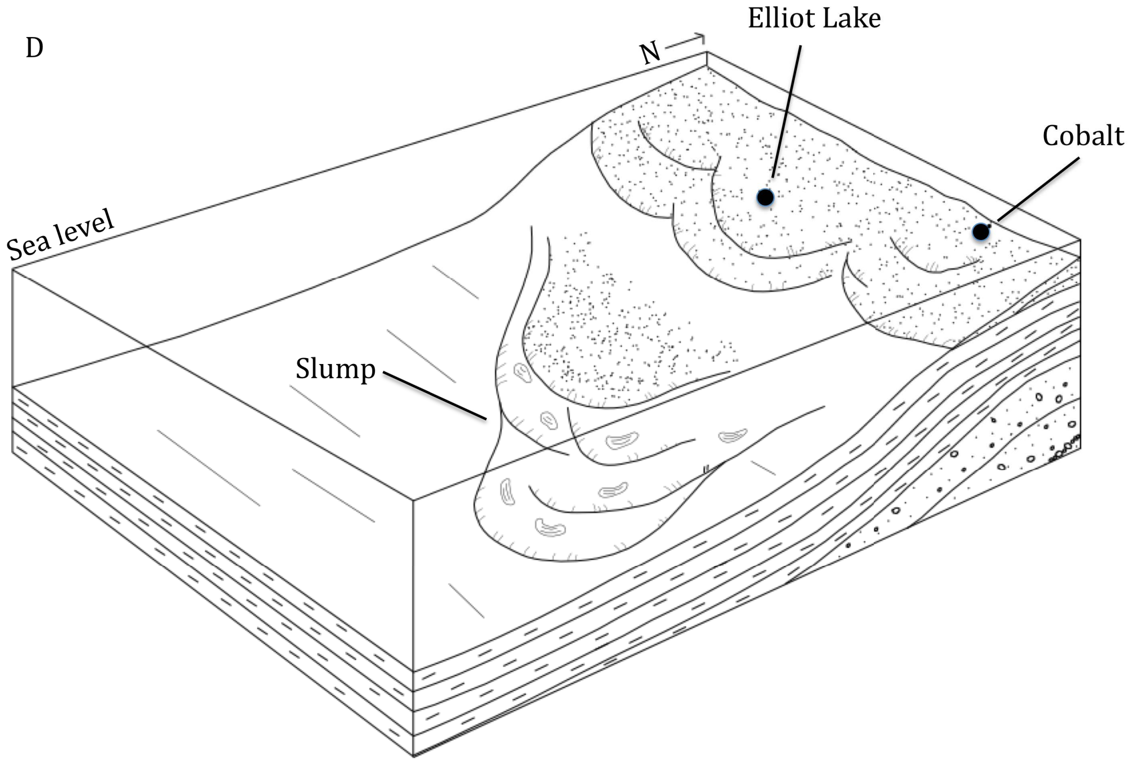
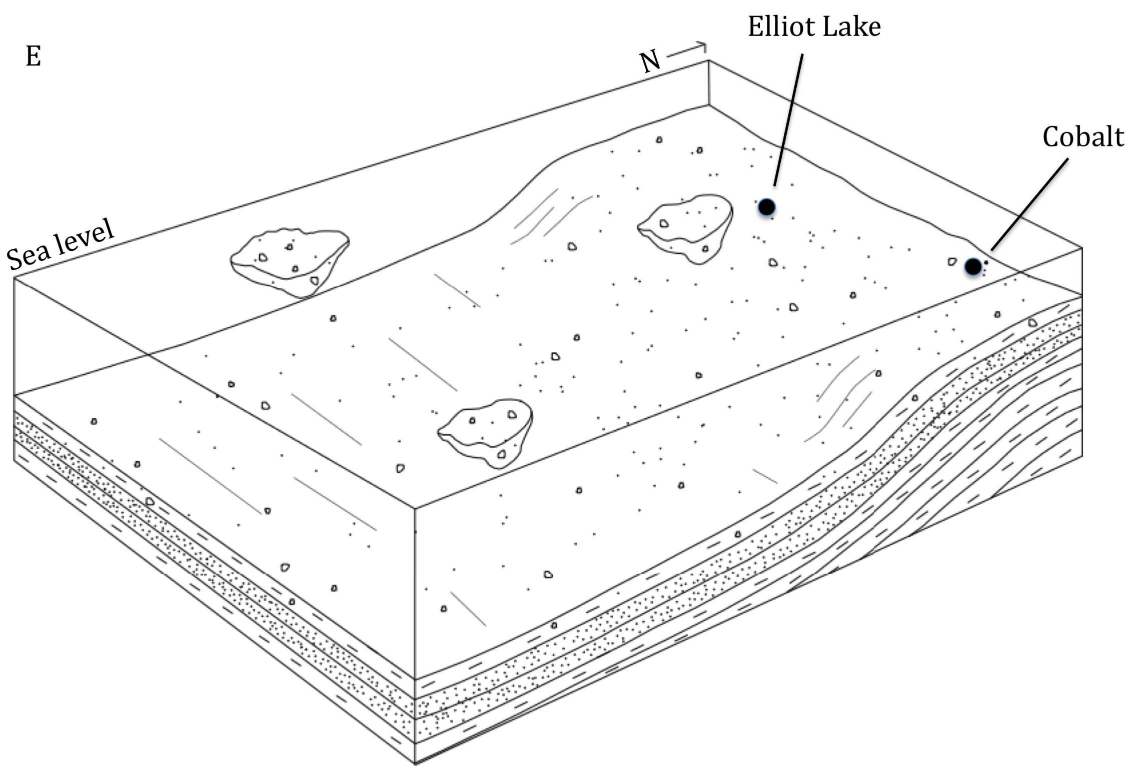


Figure 8.2 Simplified schematic models that show the evolution of the deposition environments along the Paleoproterozoic ice margin of the Gowganda Formation. A) The shallow marine depositional environment of the Planar Cross-Stratified Sandstone LA (sandwaves are not to scale). B) The open water depositional environment of the Diamictite LA. An ice front likely advanced from the north during this time and large-scale mass-flow events, as well as rainout sedimentation from overlying ice sources was common. An irregular basin floor beneath the grounded ice could account for the variability of the Diamictite LA in the Cobalt study area. C) The prodelta depositional environment of the Interlayered Siltstone and Fine-Grained Sandstone LA. An ice front retreat occurred at this time and suspension settling of the fine-grained sediments dominated. D) The Heterogeneous Sandstone LA of distal bars began to build out over the prodelta sediments. The weight of the sands or tectonic activity attributed to the isostatic rebound of the continent could have destabilized the prodelta sediments resulting in large-scale slump events. E) The second succession of the Diamictite LA represents a second glacial advance. This second glaciation was not as extensive nor as long. F) The second succession of prodelta sediments is attributed to the retreat of the second glacial front. G) A progressive return to the shallow marine depositional environment of the Quartz-Rich Sandstone LA (sand dunes are not to scale).

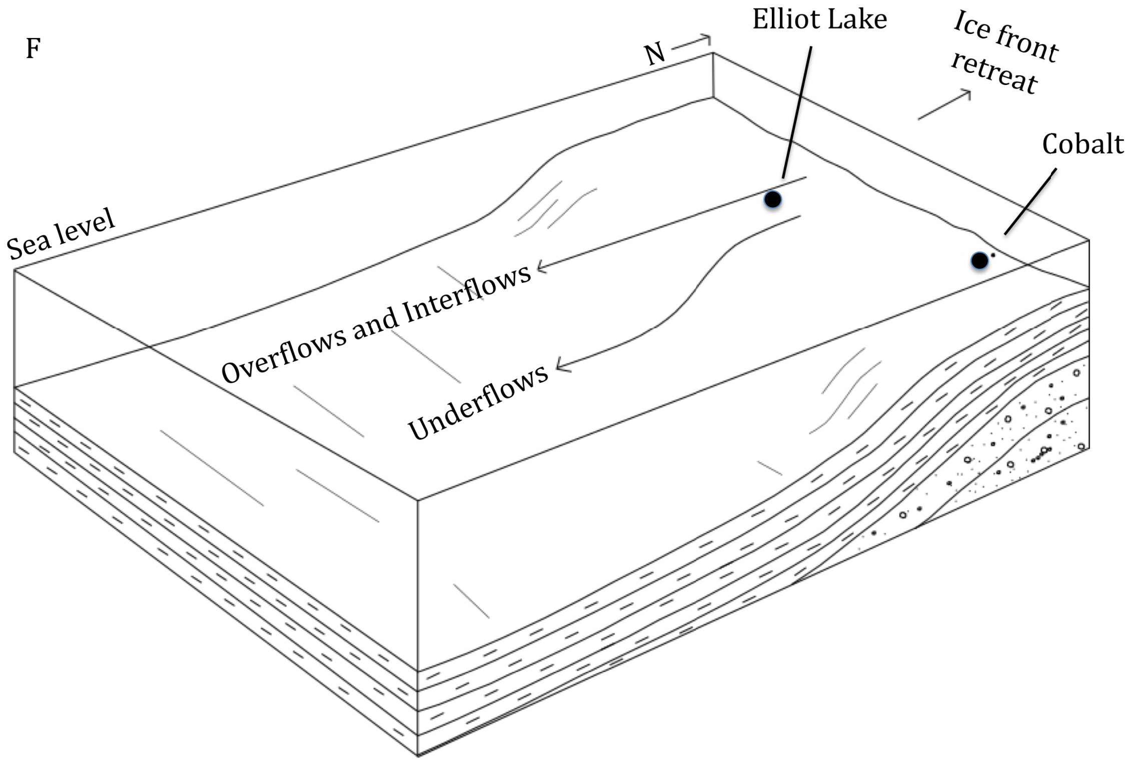

B
Icebergs
Possible Ice Shelf
N
Elliot Lake
Cobalt
Sea level
Archean
Grounded Ice
Mass-flow events


C
N
Elliot Lake
Ice front retreat
Cobalt
Sea level
Overflows and Interflows
Underflows


D
N
Elliot Lake
Cobalt
Sea level
Slump


E
N
Elliot Lake
Cobalt
Sea level

F


N
Elliot Lake
Ice front retreat
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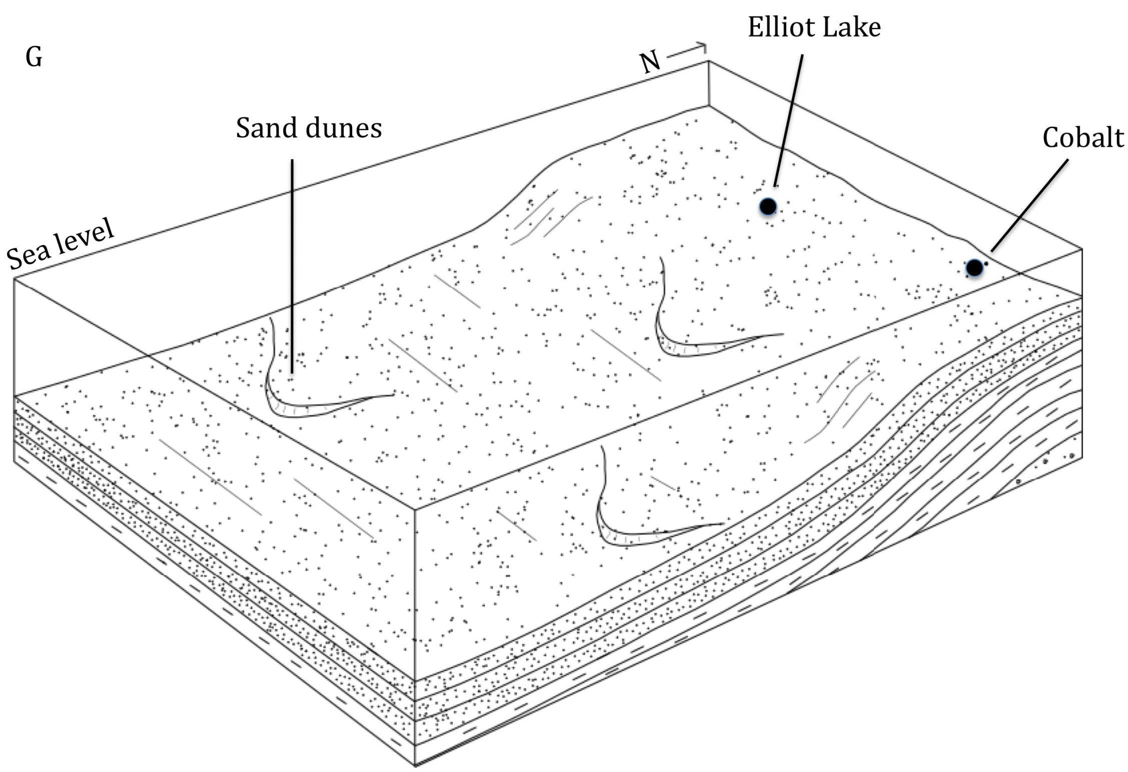
Sea level
Overflows and Interflows
Underflows

G


N
Elliot Lake
Sand dunes
Cobalt
Sea level

9. <u>SUMMARY</u>

The following chapter gives a brief overall summary of the lithofacies associations (LA) present in the study area and their relationships on a regional scale in terms of possible depositional environments (Fig. 9.1).

The upper Serpent Formation, represented by the Planar Cross-Stratified Sandstone LA, was deposited in a shallow marine, sand-dominated environment with abundant evidence of storm and wave activity. This LA is present in the southern-most study areas of Espanola and Elliot Lake where it appears to conformably underlie the Gowganda Formation. However, it is not present to the north in the Cobalt study area where the Basal Breccia LA is evidence for grounded ice. It is also not present in the study area north of Thessalon where the Gowganda Formation sits atop an unconformity with the Archean, nor is it present in the Marquette study area where the exposures are minimal and unconformably underlain by Archean rocks. The limited preservation of this LA is thought to be a result of subaerial exposure in certain areas at the time of deposition (Young, 1981a; Young, 1981b). The abundant carbonate clasts present in Gowganda conglomeratic layers in the Espanola study area indicate that the Espanola Formation, which underlies the Serpent Formation, underwent erosion to the north during ice advance. It is reasonable to assume that the Serpent Formation was also subjected to an erosive event. Possible subaerial exposure coupled with erosive events could explain the inconsistent preservation of the Planar Cross-Stratified Sandstone LA.

The Cobalt study area is the only location where the Basal Breccia LA is present at the base of the Diamictite LA indicating a period of deposition from grounded ice. This erosive LA indicates that during the Gowganda glaciation the ice front likely advanced south, past the Cobalt study area.

The first succession of the Diamictite LA in all of the study areas appears to be a result of rain-out deposition interrupted by episodes of mass-flow. The mass-flows result in the commonly channelized, well-sorted sandstone and clast-supported conglomerate layers. In the Thessalon study area, a lack of evidence for grounded ice makes the environment difficult to place for certain with respect to the ice margin. However, thick successions of massive diamictite with fewer mass-flow layers relative to the Elliot Lake and Espanola study areas could be interpreted to indicate that an ice shelf extended out over this area. Ice shelves can be responsible for large amounts of sediment raining out onto the ocean floor and ultimately decrease the current activity possibly explaining less evidence of current reworking in the area (Thomas, 1979). Both the Elliot Lake and Espanola study areas show evidence for a gradual transition from the underlying Serpent Formation. This indicates grounded ice was likely not present in these study areas. Abundant rain-out and mass-flow deposits in the form of sorted sandstone and conglomerate layers compose the majority of the LA in these study area. The rain-out deposits that persist throughout the LA indicate the presence of an overlying ice source. Evidence of current reworking throughout the diamictite layers indicates that the ice source was more likely icebergs floating in an open water environment rather than an ice shelf dampening the current activity. Considering these environmental characteristics, the mass-flow layers are most likely the result of sediments that were originally deposited closer to the ice source being remobilized into a deeper water setting. The Marquette study area differs from the other study areas in that only the Diamictite LA correlates with the Gowganda Formation. In this particular study area, the LA is similar in thickness to the other study areas but is dominated by finer-grained siltstone. The siltstone is most commonly parallel laminated from suspension settling with evidence of rain-out sedimentation from ice-rafted debris. However, there are fewer mass-flow events. This area may have been located further from the sediment source accounting for the decreased sandstone and conglomerate mass-flow layers in comparison to the abundance of them in the Espanola and Elliot Lake study areas.

The Diamictite LA gradually transitions into the prodelta-like sediments of the Interlayered Siltstone and Fine-Grained Sandstone LA in Espanola, Elliot Lake and north of Thessalon. These fine-grained sediments are indicative of deposition dominated by suspension settling in an open water environment, evidenced by the presence of some hummocky cross-stratification. The dropstones die-out stratigraphically upsection meaning there was a gradual decrease in the amount of ice-rafted debris being introduced into the environment. The decrease of ice-rafted debris most likely correlates to a retreat of the ice front and a transition into more interglacial-like sedimentation. In each of the study areas these prodelta sediments coarsen upwards into the Heterogeneous Sandstone LA.

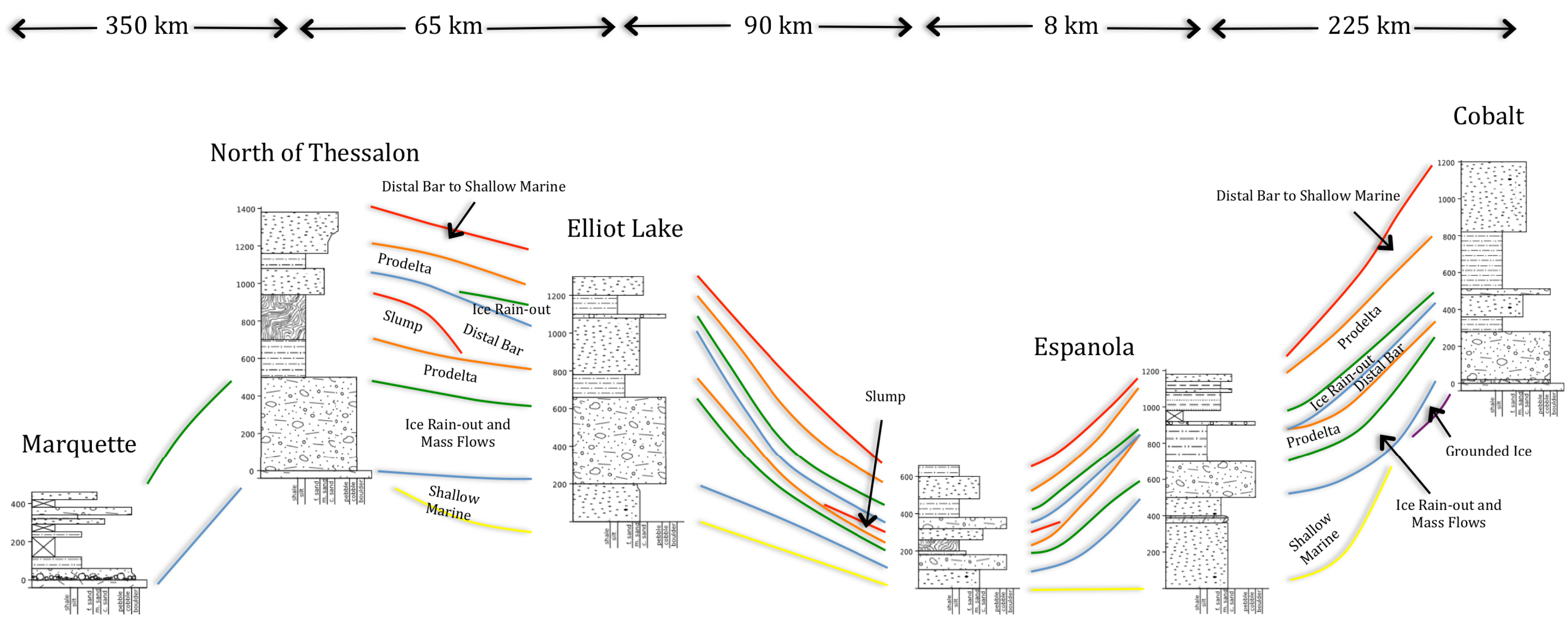


Figure 9.1 A fence diagram showing the possible regional correlations made between each of the study areas in terms of the environment of deposition for each lithofacies association.

This coarsening upwards transition is common to prograding deltaic environments as the sediments of the distal bar build out over the finer-grained, deeper water sediments of the prodelta. This clear transition into prodelta sediments is not present in the Cobalt study area. It is hypothesized ice was present for longer in this study area as it was originally to the north of the ice front, evidenced by the presence of grounded ice. Miall (1983) interprets the ice front retreat in the Cobalt study area to be indicated by an increase in mass-flow deposits on what were likely numerous subglacial outwash fans.

The Slump LA is closely associated with the prodelta sediments in both the Espanola and the Thessalon areas. Although the Slump LA is quite thick in the Espanola study area, it was not present in the northern section that was logged in this area on Iroquois Bay. This indicates these mass movements are likely isolated events and not margin-wide.

The second succession of the Diamictite LA follows the distal bar sediments of the Heterogeneous Sandstone LA indicating a re-advance of the glacial front. This second succession is much thinner than the first and identified only in the Espanola and Elliot Lake study areas, therefore it was likely not as long lived nor as widespread as the first glacial advance. In the Espanola and Elliot Lake study areas, this second succession of the Diamictite LA is dominated by rain-out debris indicating icebergs were likely the dominant sediment source. The reason for the lack of these deposits in the Thessalon study area is unclear. A glacial re-advance is a large-scale, margin-wide event and depositional environments leading into and out of the second glacial advance in the Elliot Lake and Espanola study areas can be correlated with those in

Thessalon. Similar glaciogenic deposits should be present in the Thessalon study area if grounded ice or an ice shelf developed. In contrast, if icebergs were the major source of ice rainout debris the thick distal bar succession in the Thessalon area may represent a delta platform too shallow for iceberg entry. It is also possible that, at this time, the ice front advanced from a different direction than the initial glaciation ultimately placing the Thessalon study area further from the ice source and beyond the zone influenced by ice rain-out processes. The correct reason for the lack of the second glacial advance deposits in the Thessalon area is difficult to determine. A return to massive layers of diamictite in the Cobalt study area during this time could be explained by the possible presence of an ice sheet extending over the Cobalt study area.

Following the second succession of the Diamictite LA, the prodelta-like sediments of the Interlayered Siltstone and Fine-Grained Sandstone LA are again present in the Espanola and Elliot Lake study areas. There is also a return to prodelta-like sediments following the Heterogeneous Sandstone LA in the study area north of Thessalon. This deeper water environment is thought to be present due to the isostatic loading that occurred when the glacial front re-advanced. This second succession of the prodelta-like sediments transitions upwards into another distal bar environment and then ultimately the shallow-marine sediments of the Quartz-Rich Sandstone LA. This coarsening upwards trend is again likely attributed to a prograding delta along the continental margin. This second succession of prodelta-like sediments could possibly be correlated to the Firstbrook Member of the Cobalt study area. The Firstbrook Member is interpreted to be one postglacial deltaic sequence that coarsens upwards into the basal portion of the Lorraine Formation (Rainbird and Donaldson, 1988). A margin-wide transition into deltaic environments marks the second and final retreat of the Gowganda ice front.

The second succession of the Heterogeneous Sandstone LA is present in the Espanola, Elliot Lake and Thessalon study areas to varying degrees. This LA likely represents a second progradation of the distal bar over the underlying Interlayered Siltstone and Fine-Grained Sandstone LA. This LA is not as prounounced in the Cobalt study area and was likely grouped with the Quartz-Rich Sandstone LA as the transition into the shallow marine shelf environment was a gradual one.

The Quartz-Rich Sandstone LA of the basal Lorraine Formation truly represents a return to a shallow marine, sand-dominated shelf environment. The gradual transition from the underlying Heterogeneous Sandstone LA in the Espanola, Elliot Lake and Thessalon study areas shows that on a regional-scale, this margin was likely a prograding shoreline changing from an environment dominated by sedimentation in a distal bar to one dominated by mature, cross-stratified sandstones typical of a current dominated shelf environment. The glacially related deposits in the Marquette study area are stratigraphically overlain by the Mesnard Quartzite, a sandstone dominated unit with cross-stratification, ripple cross-lamination and beds up to a few meters thick (Puffett, 1974). The return to a sand dominated, shallow-marine shelf environment also occurred in the Marquette region as it did in the other study areas.

10. CONCLUSIONS

The Basal Breccia LA at the base of the Gowganda Formation marks a definite large-scale erosive surface, which is thought to be a result of grounded ice, between the Paleoproterozoic rocks and the underlying Archean rocks in the Cobalt study area. There is a significant amount of carbonate debris, likely from the underlying Espanola Formation, in the form of clasts incorporated into the conglomerate layers in the Espanola study area. These clasts are evidence that a large-scale erosive event likely occurred to the north of this study area. The Espanola clasts are thought to have been eroded from the partially lithified carbonate layers by overriding ice prior to being incorporated into the depositional processes of the Gowganda Formation. There is a lack of visible, large-scale erosive surfaces throughout the remainder of the Gowganda Formation indicating deposition was continuous. The following outlines a possible sequence of events that would account for the succession of lithofacies associations in each of the study areas.

The initial Gowganda ice front was most likely located to the south of the Cobalt study area (Fig. 10.1A) due to the presence of the Basal Breccia LA, evidence for the presence of grounded ice (Mustard and Donaldson, 1987a,b). There is a lack of evidence for the presence of grounded ice in the study area north of Thessalon, therefore the grounding line can not necessarily be placed to the south of this area. However, the Gowganda Formation does sit unconformably on underlying Archean rocks in this study area, indicating either some form of erosion occurred or there was simply not enough accommodation space for the underlying portion of the

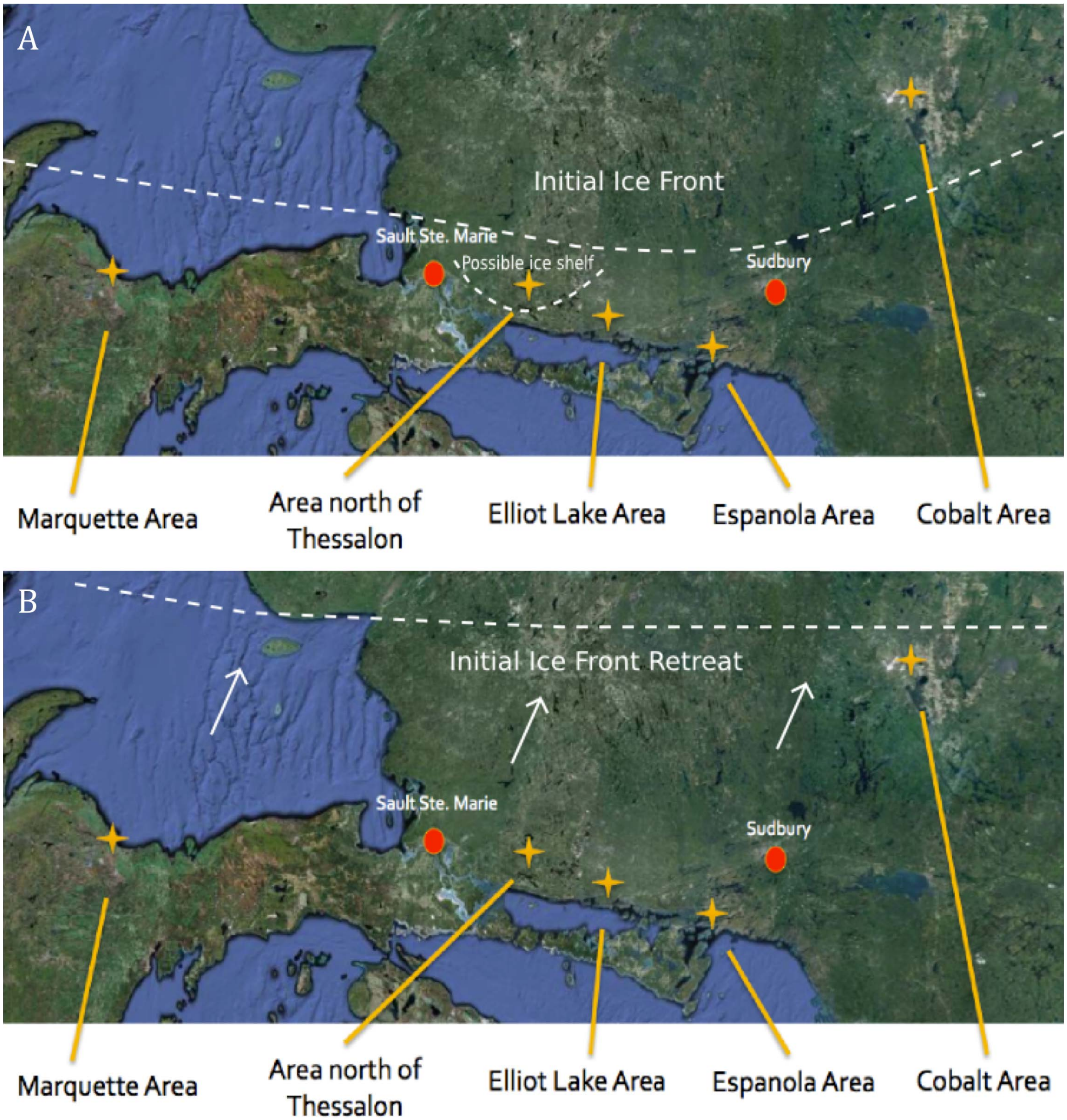


Figure 10.1 A) The proposed location of the initial ice front with a possible ice sheet extending out over the study area north of Thessalon, Ontario. B) A retreat in the ice front to a location north of all five of the study areas would account for a decrease in ice-rafted debris in the southern study areas and an increase in mass flow deposits in the north.

Huronian Supergroup to be preserved. It is plausible that this study area was initially beneath an ice sheet accounting for the accumulation of relatively thick layers of matrix-supported diamictite. Massive layers of diamictite are usually attributed to large amounts of rain-out sedimentation, common beneath ice shelves (Thomas, 1979).

An ice front located to the north of the southern study areas would account for the predominance of mass-flow deposits in the Elliot Lake and Espanola study areas (Miall, 1985). There is no evidence of grounded ice in these areas, however there is a continual presence of ice-rafted debris and current re-working of the sediments. This indicates the presence of an overlying ice source, but it is unlikely that the ice source is an ice sheet. An ice sheet would dampen the current activity and would result in massive, matrix-supported diamictite layers (Mackiewicz et al., 1984; Link et al., 1994; Visser, 1994). The sediments in these study areas were probably deposited nearer the glacial outwash source and were then remobilized by mass-flow events and reworked by current activity in an open water environment. The presence of ice-rafted debris indicates icebergs were present in this open water environment. Again, there is no evidence of grounded ice in the Marquette study area placing the grounding line somewhere to the north of that study area. The outcrops are dominated by siltstone with thin conglomerate and sandstone layers indicating they were likely in an environment distal to the glacial outwash source at the time of deposition.

A retreat of the ice front to a location north of all of the study areas (Fig. 10.1B) would place each region further away from the ice source. This retreat would account for the decrease in ice-rafted debris and the prodelta-like sediments of the Interlayered Siltstone and Fine-Grained Sandstone LA and the Slump LA that are present particularly in the Thessalon, Elliot Lake and Espanola study areas. In each of these areas, the prodelta-like sediments follow the coarsening-upwards trend documented in deltas from the prodelta to the distal bar environments. An ice front retreat in the Cobalt study area is indicated by the presence of abundant mass-flow deposits likely caused by the resedimentation of subglacial outwash on numerous outwash fans in the area (Miall, 1983). It is difficult to correlate the timing of ice retreat in the Cobalt study area for certain with the timing of the ice retreat in the southern study areas (Junnila and Young, 1995). However, it does seem plausible that the shift from basal or lower englacial transport to mass-flow deposits could be caused by the same glacial retreat that caused the shift to the prodelta-like environments in the southern study areas.

A re-advance of the ice front is marked by a second succession of the Diamicitite LA. This second glacial advance was shorter lived than the first as indicated by the thinner second succession of the Diamictite LA in the Elliot Lake and Espanola study areas. A lack of evidence of grounded ice likely places the ice front at this time to the north of all of the study areas (Fig. 10.2A). In the Cobalt study area, the presence of massive layers of continuous, matrix-supported conglomerate indicate an ice sheet may have extended over the area at this time. As previously mentioned, massive layers of diamictite are common beneath ice shelves (Thomas, 1979). A second succession of the Diamicitite LA was not present or was not located in the study area north of Thessalon. In the Espanola and Elliot Lake study areas the deposits of the second advance are dominantly iceberg related therefore, the same would be expected in the Thessalon study area. The reason for the lack of these deposits in this area is unclear. Being as the second advance did not deposit as thick a succession of sediments and therefore was not as long lived as the first, it is plausible that it was not as extensive as the first advance. It is

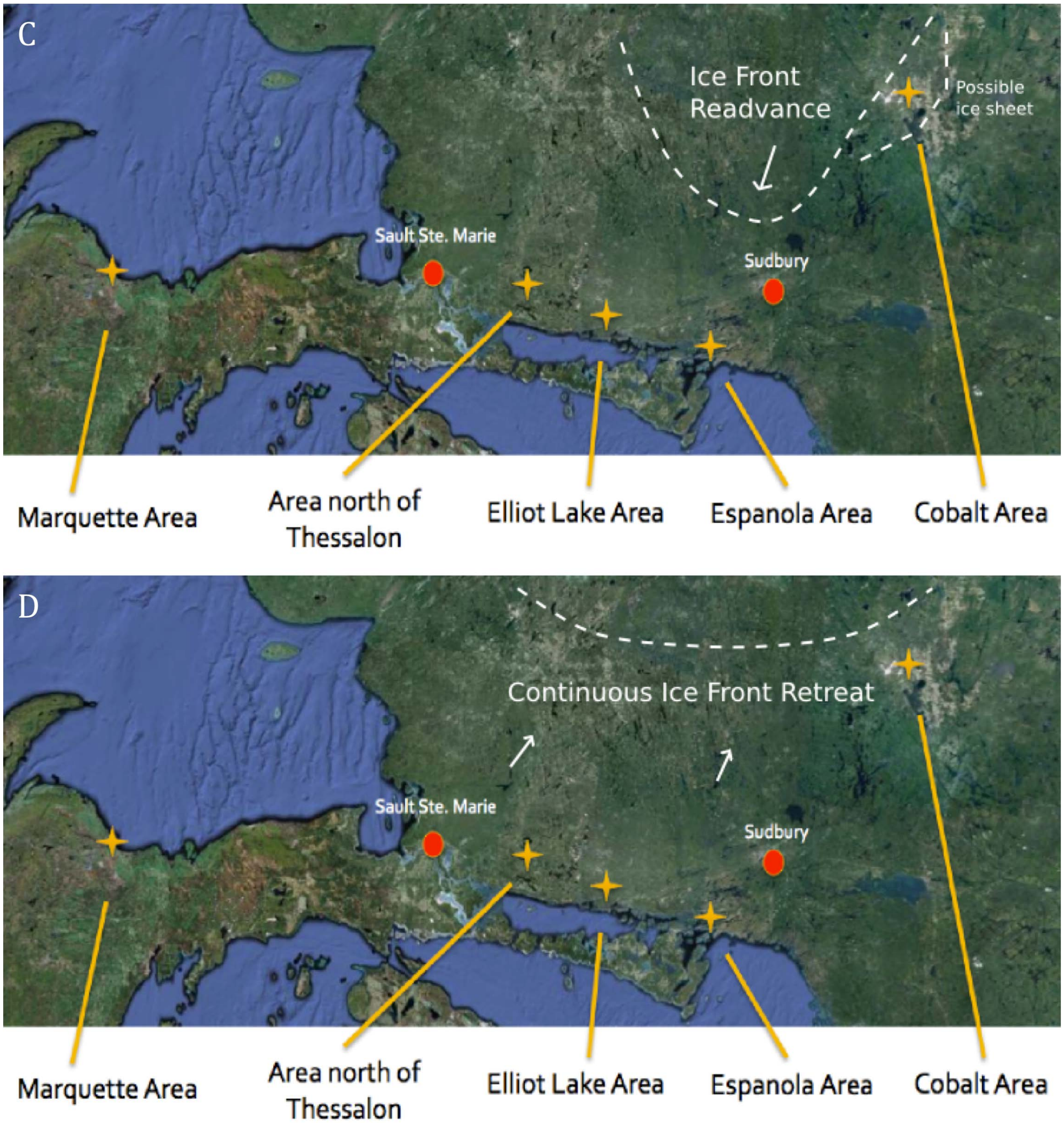


Figure 10.2 A) A short-lived readvance of the ice front would account for the second succession of the diamictite lithofacies association. A possible ice sheet extending over the Cobalt study area could be responsible for the massive layers of diamictite accumulating in that area. B) A continuous ice front retreat would allow for the accumulation of a deltaic sequence that would build stratigraphically upsection into the shallow marine depositional environment of the Lorraine Formation.

therefore possible that at this time, the ice front advanced from a different direction than the initial glaciation ultimately placing the Thessalon study area further from the ice source and beyond the zone influenced by ice rain-out processes. It is also possible that the Thessalon area was too shallow to allow iceberg transport of sediment.

Following the second, short-lived advance of the ice front, a continuous glacial retreat likely occurred (Fig. 10.2B). This is most evident due to the presence of the prodelta-like sequences in each of the study areas that coarsen progressively upwards into the shallow-marine sediments of the basal Lorraine Formation. In the Espanola study area, Junnila and Young (1995) documented more than one coarsening upwards sequence of deltaic sediments present in the uppermost portion of the Gowganda Formation. This was thought to be a result of deposition in migrating delta lobes (Junnila and Young, 1995). In the Cobalt study area, the Firstbrook Member indicates the presence of one coarsening upwards, postglacial deltaic sequence that was deposited during the rising sea levels (Rainbird and Donaldson, 1988). In the study area north of Thessalon, as well as in Espanola, hummocky cross-stratification was present in the uppermost portions of the Gowganda Formation indicating the shift to a shallow marine depositional environment influenced by storm activity.

The Marquette study area does not have as continuous, nor as extensive outcrop exposures as the other study areas making it difficult to correlate. The continued presence of ice-rafted debris throughout the outcrops of the Marquette study area indicates it would most likely be correlated to the lower portion of the Gowganda Formation instead of the upper portion, which has no evidence of ice-rafted debris in the other study areas. This is consistent with the interpretation of the Marquette study area as a subaqueous glacial outwash fan supplied predominantly by siltstone in an environment relatively distal to the outwash source. The glacially related deposits in the Marquette study area interestingly enough are stratigraphically overlain by the Mesnard Quartzite, a sandstone dominated unit with cross-stratification, ripple cross-lamination and beds up to a few meters thick (Puffett, 1974). This is evidence that there was a transition to a sand dominated, shallow-marine environment in the Marquette area, just as in the other study areas.

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APPENDIX

Core Logs

Hole	From (m)	To (m)	Lithology
150-1	0	11.3	Conglomerate
	11.3	16	Conglomerate
	16	66	Conglomerate
	66	83	Medium- to Coarse-Grained Sandstone
	83	97	Conglomerate
	97	101	Conglomerate
	101	104	Medium- to Coarse-Grained Sandstone
	104	105	Siltstone
	105	108	Medium- to Coarse-Grained Sandstone
	108	117	Conglomerate
	117	120	Medium- to Coarse-Grained Sandstone
	120	124	Siltstone
	124	125	Medium- to Coarse-Grained Sandstone
	125	218.5	Conglomerate
	218.5	219	Lamprophyre
	219	291.4	Conglomerate
	291.4	309	Fine- to Medium-Grained Sandstone
	309	310	Lamprophyre
	310	321	Fine- to Medium-Grained Sandstone
	321	344	Fine- to Medium-Grained Sandstone
	344	345	Lamprophyre
	345	415	Medium- to Coarse-Grained Sandstone
	415	417	Lamprophyre
	417	445	Fine-Grained Sandstone
	445	455	Coarse-Grained Sandstone
	455	455.5	Conglomerate
	455.5	456	Lamprophyre
	456	460	Fine- to Very Coarse-Grained Sandstone
	460	537	Medium- to Coarse-Grained Sandstone
150-4	6.7	9.5	Diabase
	9.5	125	Medium- to Very Coarse-Grained Sandstone
	125	132.6	Fine- to Medium-Grained Sandstone
	132.6	157.6	Siltstone
	157.6	195	Fine- to Coarse-Grained Sandstone interbedded with Siltstone
	195	222.8	Fine- to Medium-Grained Sandstone
	222.8	356	Conglomerate
	356	451.6	Fine- to Coarse-Grained Sandstone interbedded with Conglomerate

	451.6	633.7	Conglomerate
	633.7	681.5	Fine- to Medium-Grained Sandstone
	681.5	700.1	Fine- to Medium-Grained Sandstone
	700.1	839.1	Fine- to Medium-Grained Sandstone
TME07-02	4	17	Medium- to Coarse-Grained Sandstone
	17	29.2	Coarse-Grained Sandstone
	29.2	29.6	Conglomerate
	29.6	37.4	Medium-Grained Sandstone
	37.4	48.4	Interlayered Siltstone and Silty-Sandstone
	48.4	80.3	Diabase
	80.3	82	Siltstone
	82	106	Fine- to Medium-Grained Sandstone
	106	120.8	Conglomerate
	120.8	129.3	Siltstone
	129.3	159.5	Conglomerate
	159.5	161.4	Coarse-Grained Sandstone
	161.4	174.1	Interlayered Siltstone and Silty-Sandstone
	174.1	182	Siltstone
TME07-03	3	15.7	Fine- to Medium-Grained Sandstone
	15.7	36	Interlayered Siltstone and Silty-Sandstone
	36	53	Siltstone
	53	65.3	Fine- to Medium-Grained Sandstone
	65.3	93.8	Conglomerate
	93.8	99.4	Granite
	99.4	122.5	Siltstone
	122.5	145.9	Siltstone
	145.9	152.2	Conglomerate
	152.2	159	Conglomerate
	159	199	Siltstone
	199	264	Tonalite, Granodiorite, Trondjemite
TME08-17	2.3	166.1	Diabase
	166.1	172.6	Conglomerate
	172.6	201.3	Interlayered Siltstone and Mudstone
	201.3	202.4	Medium-Grained Sandstone
	202.4	207	Conglomerate
	207	220.4	Interlayered Siltstone and Mudstone
	220.4	223	Fine- to Medium-Grained Sandstone
	223	223.4	Mudstone
	223.4	234.8	Fine- to Coarse-Grained Sandstone
	234.8	248.8	Conglomerate
	248.8	262	Interlayered Siltstone and Mudstone
	262	268.1	Conglomerate
	268.1	273.3	Medium-Grained Sandstone
	273.3	287.4	Conglomerate

	287.4	288.3	Interlayered Siltstone and Mudstone
	288.3	298.5	Conglomerate
	298.5	321.1	Conglomerate
	321.1	325.2	Conglomerate
	325.2	335.3	Fine- to Coarse-Grained Sandstone
	335.3	336	Conglomerate
	336	340.8	Interlayered Siltstone and Mudstone
	340.8	344.7	Conglomerate
	344.7	350	Tonalite, Granodiorite, Trondjemite