A SEDIMENTOLOGICAL INVESTIGATION OF THE SUNNYBROOK DIAMICT, SCARBOROUGH BLUFFS, REGION, ONTARIO, CANADA

Degree: Master of Science 1995
Department of Geography
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A SEDIMENTOLOGICAL INVESTIGATION OF THE SUNNYBROOK DIAMICT, SCARBOROUGH BLUFFS REGION, ONTARIO, CANADA

By

TODD ANDREW RANDALL, B.Sc.

A thesis

Submitted to the School of Graduate Studies

in Partial Fulfilment of the Requirements

for the Degree

Master of Science

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ABSTRACT

Exposures of Quaternary-aged sediments along the Scarborough Bluffs, near Toronto, provide considerable information concerning environmental conditions which existed during the last interglacial-glacial cycle along the southern margin of the Laurentide Ice Sheet. The present exposures dissect a thick interglacial deltaic body (Scarborough Formation), overlain by a set of interfingered fine-grained diamicts (Sunnybrook, Seminary, Meadowcliffe, Halton) and interstadial sands (Thorncliffe Formation). The depositional origin of the diamicts have been vigorously debated in the literature, particularly that of the Sunnybrook.

Two facies associations for the Sunnybrook are introduced in this study, Channel (CFA) and High Facies Association (HFA), based upon: facies and contact descriptions, and contact geometries. The CFA consists of a thick package (10-18m) of massive and stratified diamicts, conformably overlain by a succession (11-25m thick) of finely and coarsely bedded turbidites, and infills topographic lows within the underlying strata. Silt clast breccia, flow noses, debris flow deposits, and turbidites, within the CFA, are proof of a subaqueous resedimentation origin. The HFA is located on the relative highs, away from channels, forming horizontally-planar contacts with the underlying Scarborough Formation. The HFA consists of an association of: massive and stratified diamicts, and deformed laminated silts and clays. In addition, the HFA has several unique characteristics which include: basal clast horizons, an interbedded contact zone (ICZ), and reverse density loading along the upper contact of the Sunnybrook with the overlying Lower Thorncliffe Formation.

The proposed depositional model for the Sunnybrook's two facies associations suggests combined rain-out from suspended sediment plumes and from ablating ice masses, and resedimentation in a glaciolacustrine setting. As well, a model of formation for basal clast horizons in the HFA was developed in this study. A subaqueous interpretation of the Sunnybrook implies the existence of a high level lake, in the Metro Toronto Region, for the duration of the early and middle Wisconsin period. Previous interpretations, which suggest subglacial conditions during deposition of the Sunnybrook and related diamicts, are not substantiated by the sedimentological and glaciotectonic data of the present study.

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CHAPTER 1: INTRODUCTION

1.1 OVERVIEW

Extensive outcrops of Late Quaternary sediments are exposed along the north shore of Lake Ontario at the Scarborough Bluffs (**Fig. 1.1**) and provide a key site for the interpretation of glacial environments associated with the southern margin of the Laurentide Ice Sheet during the last glacial cycle (Sangamon - Wisconsin). The exposures at Scarborough are comprised of four major geological units: Scarborough Formation, Sunnybrook Drift, Thorncliffe Formation and Halton Till. The Scarborough Formation is a coarsening upwards deltaic succession deposited in early Wisconsin time (Clark, 1986), and is dissected, in places, by several large channels. The Sunnybrook Drift, of presumed mid-Wisconsin age, is a diamict unit of variable thickness and forms a drape over the irregular geometry of the Scarborough Formation. Overlying the Sunnybrook Drift are a succession of interbedded diamict and sand units; the sands are regionally exposed and collectively identified as the Thorncliffe Formation while the diamict units (Seminary and Meadowcliffe) are limited to exposures along the Bluffs. The Thorncliffe Formation is overlain either by the late Wisconsin Halton Till or by post-glacial Lake Iroquois sediments. Exposures at the Scarborough Bluffs provide one of the most complete records of the last interglacial-glacial transition in eastern North America and are significant for

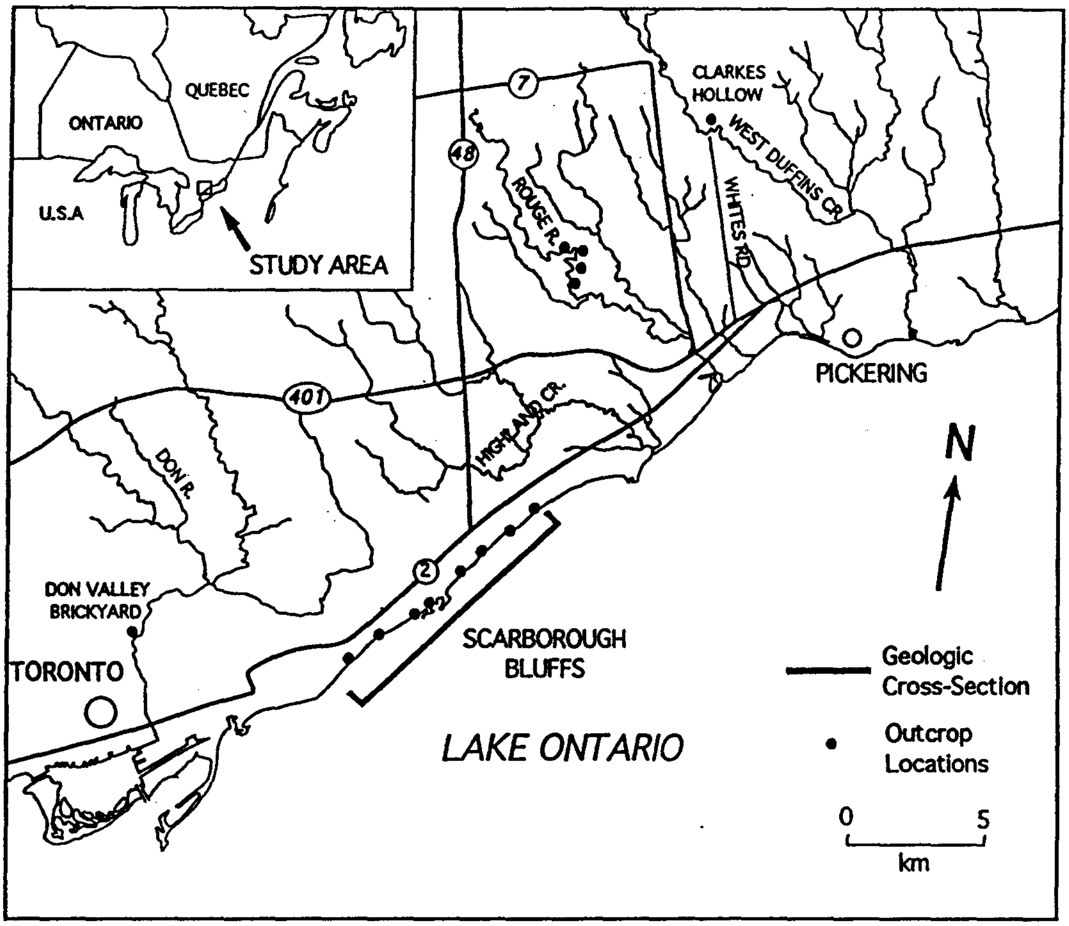


Figure 1.1: Study area showing approximate section locations at Scarborough Bluffs, Rouge River and Duffins Creek. More precise section locations are indicated in Figure 2.1.

the interpretation of environmental conditions particularly during the early Wisconsin period. Understanding the nature of glacial palaeoenvironments helps us better understand ice sheet margin behaviour and the dynamics of large ice masses (see section 1.1.1). The present study focuses on the paleoenvironment which existed in the Lake Ontario basin during deposition of the Sunnybrook Drift.

The Sunnybrook Drift is a fine-grained diamicton of late Quaternary age which underlies much of the Metro Toronto region and is well exposed at the Scarborough Bluffs. The depositional origin of this extensive stratigraphic unit (covering approximately 3000 km^2) has been vigorously debated over the past 11 years and it has been variably interpreted as either a subglacial deposit (Karrow, 1967, 1969, 1984a; Dreimanis, 1977, 1984; Gravenor, 1984; Hicock and Dreimanis, 1989, 1992a, 1992b; Sharpe, 1984) or a glaciolacustrine deposit (Eyles and Eyles, 1983, 1984; Westgate et al., 1987; Rutka and Eyles, 1989; Schwarcz and Eyles, 1991). Each of these interpretations has major implications for our understanding of the dynamics of the Laurentide Ice Sheet during the last major glaciation (Wisconsin) in North America. Karrow (1967) and Hicock and Dreimanis (1989; 1992a) support a subglacial origin for the unit, suggesting the Sunnybrook was deposited predominantly as a lodgement or deformation till, recording extensive ice advances in the Lake Ontario basin during the early-mid Wisconsin. A subglacial origin for the Sunnybrook implies full ice cover over the Ontario basin, a more southerly position for the actual ice margin and a relatively severe 'glacial' climate. An alternate origin, proposed by Eyles and Eyles (1983), suggests a glaciolacustrine depositional setting for the Sunnybrook. A glaciolacustrine origin requires that the Ontario basin be water-filled with floating glacier ice <u>somewhere</u> in the basin, and introduces the possibility of a more distal ice margin during Sunnybrook time and less severe climatic conditions at Toronto.

The Sunnybrook drift has been examined by many geologists, but has not been subjected to a detailed regional sedimentological study. This study aims to resolve some of the controversy surrounding the origin of the Sunnybrook through detailed sedimentological analysis of the unit at exposures along the Scarborough Bluffs and along the eroded banks of several creeks that flow into Lake Ontario to the east of the Bluffs (**Fig. 1.1**). It is hoped that this detailed regional sedimentological analysis will provide information about the broad range of palaeoenvironments that existed during Sunnybrook time and not just local conditions. These data will be used to construct a depositional model for the Sunnybrook that may be used to distinguish glaciolacustrine environments from subglacial environments in both the sediment and rock records.

1.1.1 SIGNIFICANCE OF THE PROPOSED RESEARCH

The activities of glaciers during the Quaternary in Canada has created a variety of landscapes. Approximately 80% of Canada's terrain has been subjected to glacier ice at least once over the past 1 million years (Ford et al., 1984). Glacial landscapes include both barren areas (e.g. Canadian Shield), scraped clean of sediments and vegetation, and areas with vast thicknesses of glacial drift (e.g. thick Pleistocene sequences in southern Ontario and thick valley fills of glacially-derived sediment in British Columbia). Pleistocene glacial-lake sediments cover large areas of Canada; for example, Glacial Lake Agassiz occupied an area of more than 1 million km^2 during the retreat of the Laurentide Ice Sheet (Teller, 1987).

The importance of developing depositional models for glacigenic sediments is threefold: 1) for past climatic reconstruction, 2) for interpreting past glacier behaviour, and 3) for defining and predicting lateral and vertical variability in glacial deposits. The Earth has been subjected to cyclical warming and cooling trends during and before the Quaternary period. Understanding past climatic fluctuations and their forcing mechanisms may allow greater understanding of predicted climatic changes (Ellsaesser et al., 1986; COHMAP, 1988). Many theoretical models of glacier behaviour (e.g. Boulton and Hindmarsh, 1987) are making good progress in predicting ice sheet dynamics and bed conditions. However, these models need more ground truthing. The sedimentological analysis of the Sunnybrook Drift presented in this thesis may help to clarify climatic conditions which existed during the Wisconsin at the Scarborough Bluffs. The advantage of studying exposures of Pleistocene glacial deposits to better understand the nature of sedimentological processes and deposits in glacial environments is that glacial environments are often inaccessible (e.g. subglacial or subaqueous ice-proximal environments) or do not exist today (e.g. large ice-proximal lakes).

Understanding the stratigraphic and spatial variability of glacial deposits is also important in 'applied' aspects of glacial geology. Spatial and vertical variations in texture, degree of fracturing, and geometry of the deposits have impacts for land use and pollution remediation schemes (Eyles, N. et al., 1992). Many aquifers in Pleistocene deposits, are composed of glaciofluvial outwash deposits or moraines (e.g. the Oak Ridges moraine, north of Toronto), but such aquifers are often threatened by urban and agricultural uses (Domenico and Schwartz, 1990). Near-surface aquitards (both glacial lake sediments and fine-grained diamictons and tills) provide the necessary "buffer protection layer" for underlying and presently unpolluted aquifers but also are thought to be suitable hosts for sanitary landfills (Hibbert, 1993). Unconsolidated fine-grained glacial sediments are also subject to mass movement processes, causing often unpredicted consequences to anthropogenic activities. Landslide, bluff erosion and slope failure are common in glacial landscapes underlain by glaciolacustrine sediments (Evans, 1982; Eyles, N. et al., 1985). The facies characteristics, facies associations and geometry of the Sunnybrook discussed in this thesis may be helpful in both of these applied aspects: 1) in predicting stability conditions, and 2) in understanding the groundwater flow patterns associated with these glacial landscapes.

1.2 QUATERNARY GEOLOGY

1.2.1 OUTCROP AREAS

The Sunnybrook diamict underlies most of the Metro Toronto region and is well exposed along 12 km of lakeshore bluffs (the Scarborough Bluffs) which lie to the east of Toronto, between Warden Ave (in the west) and Beechgrove Drive (in the east; **Figs. 1.1** and **1.2**). Other important outcrops occur along the banks of creeks and rivers which flow into Lake Ontario in the Metro Toronto region (e.g. Highland Creek, Duffins Creek, and Rouge River; **Fig. 1.1**). The Sunnybrook is also exposed in the Don Valley Brickyard, where important interglacial deposits of the Sangamon Don Formation occur. The sections at this site are now protected from threatened development but only restricted access is available to geologists (Eyles and Clark, 1988a), and they have become covered by slumped material; the Don Valley sections are therefore not included in this study. The status of exposures at Scarborough Bluffs is also in jeopardy due to recent efforts to stabilize and limit erosion along the shoreline. Rates of cliff top retreat reached 1-2 metres per year in the late 1970's and early 1980's (Eyles, N. et al., 1985); as a result, large toe protection systems were built (e.g. Bluffers Park Marina, groynes and berm roads) during the 1980's which have locally reduced rates of erosion and are causing the slopes to become vegetated. The effects of these shoreline protection works has been to reduce the availability and continuity of sediment exposure along the Bluffs.

There are few exposures of the Sunnybrook to the west and northwest of

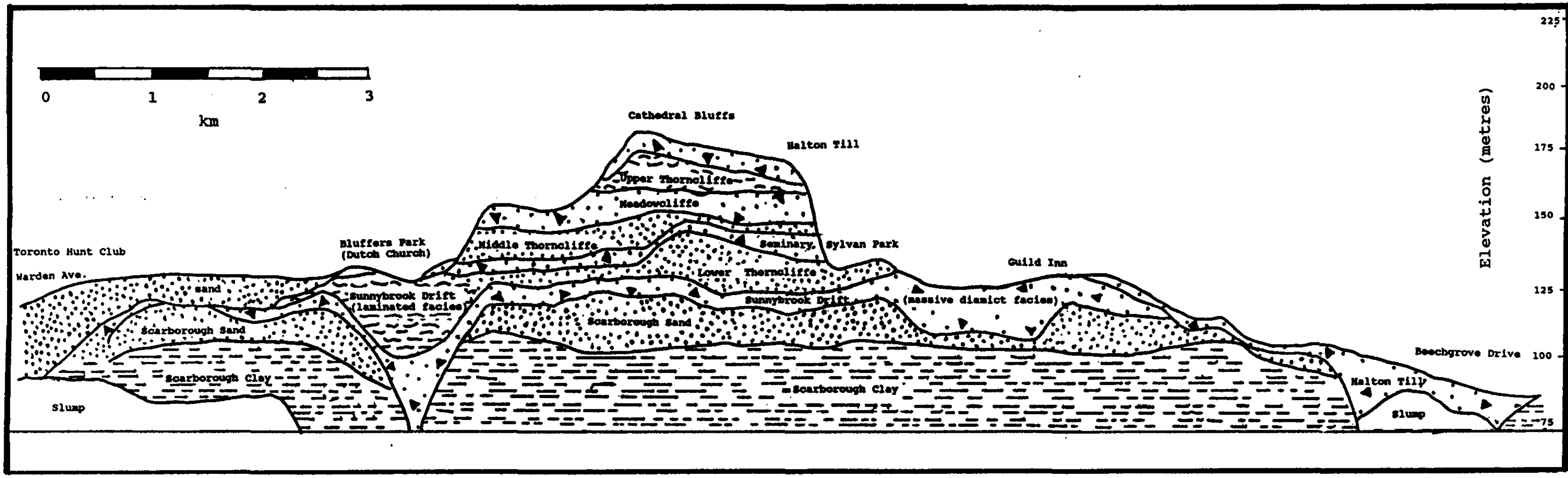
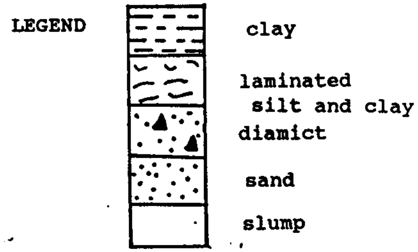


Figure 1.2: Summary cross-section of Quaternary deposits exposed at Scarborough Bluffs. The Sunnybrook Drift drapes over the Scarborough Formation, infilling several channels cut into the underlying Scarborough (e.g. at Dutch Church and Guild Inn sections). The Sunnybrook consists of two major facies types: massive diamict and laminated silt and clay. Overlying deltaic sands (Thorncliffe Formation) are interfingered with two other fine-grained diamicts (Seminary and Meadowcliffe). The entire sequence is capped by the Late Wisconsin Halton till. Selective erosion of the Bluffs occurred during the time of high-level post-glacial lakes (e.g. Lake Iroquois). Modified from Karrow (1967).



the Bluffs due to erosion by subsequent advances of Late Wisconsin ice and by removal of sediments by post-glacial lakeshore processes. Sunnybrook sediments are described in a railway cut at Woodbridge, north of Toronto by Karrow (1969) and White (1971) and in outcrops along Humber River; however, these sections are now covered and were not included in this study. To the east of the Scarborough Bluffs, a correlative deposit to Sunnybrook diamict is believed to be the Port Hope Till (Brookfield et al., 1982). The Port Hope Till outcrops at modern lake level at the Bowmanville Bluffs between Courtice and Port Hope, approximately 50 km east of Scarborough. The Port Hope Till was not included in this study due to time constraints.

1.2.2 THE INTERGLACIAL-GLACIAL STRATIGRAPHY

The stratigraphic succession exposed at Scarborough Bluffs is the primary tool for interpretation of glacial-interglacial periods during the late Pleistocene in the Ontario basin. **Figure 1.2** is a summary cross-section of the deposits exposed at the Bluffs. The Scarborough Formation forms the base of the succession and consists of a thick coarsening upwards sequence (from clays through sands) interpreted as a deltaic deposit (Karrow, 1967; Clark, 1986). This delta was deposited by a large southwardly flowing river which occupied a large ancient bedrock channel linking Georgian Bay to Lake Ontario -- part of the Laurentian Channel (Spencer, 1890). Lake level during deposition of the delta was approximately 45m above present Lake Ontario levels. The top of the delta is irregular, dissected by several large channels (up to 50m deep).

The Sunnybrook diamict forms an extensive drape up to 8-10m thick over the Scarborough Formation. Topographic lows in the top of the diamict are correlated with channels in the underlying Scarborough Formation (e.g. Dutch Church section: **Fig.1.2**); laminated facies of the Sunnybrook infill these lows. Overlying the Sunnybrook are two other diamict units (Seminary and Meadowcliffe) - exposed only at the Bluffs (Karrow, 1967) - which are interfingered with the three members (Lower, Middle, and Upper) of the Thorncliffe Formation. The whole sequence is capped by the Halton Till, which was deposited by an expanded Laurentide ice sheet covering the whole of southern Ontario during the Late Wisconsin (Karrow, 1967, 1984b; Boyce and Eyles, 1991). A large post-glacial lake (Lake Iroquois) occupied the Lake Ontario basin as the Late Wisconsin ice margin withdrew and deposited extensive units of sand and gravel identified west of Bluffers Park and east of Sylvan Park.

1.2.3 AGE OF THE SCARBOROUGH STRATIGRAPHY

Dating individual units and events that make up the stratigraphic succession at the Scarborough Bluffs is problematic. Volcanic tephra layers, which would serve as time markers and are commonly used to correlate depositional events in western North America, are not present in any of the exposed sediments. Dating of the Scarborough succession has been commonly constrained using radiocarbon dating techniques; however, most of the C-14 dates available (**Table 1.1**) are unreliable due to "old carbon errors". C-14 dates available for the Scarborough succession are mostly obtained from analysis of "aquatic plants" (Berti, 1975). This is a problem as lake waters are enriched in 'old' carbonate provided by the predominantly carbonate bedrock in the Ontario basin; aquatic plants living in the lake absorb this 'old' carbon and when dated, provide dates much older than they should, usually with errors of unknown magnitude. Reported ages (C-14) for the Lower Thorncliffe Formation, which

UNIT	C-14 dates Lowden et al.(1971); Karrow (1967)	TL dates Berger (1984)	TL dates Berger and Eyles (1994)
Halton Till		>140 ka	
Upper Thorncliffe	28.3±0.6 ka[1] 32.0±0.7 ka[2]	36±4 ka	23±4 ka
Seminary & Meadowcliffe			
Lower Thorncliffe	>53 ka[3] 45 ka[3] 38.9 ka[4] 48.8 ka[5]		
Sunnybrook		66±7 ka	41±8 ka 46±9 ka
upper Scarborough lower	 >53 ka[3]		51±9 ka 55±10 ka 60±9 ka 54±8 ka

Table 1.1: Available dates (Carbon-14 and TL) for Quaternary units exposed at the Scarborough Bluffs. Radiocarbon dates provided in Lowden et al. (1971, fide Berti, 1975) and Karrow (1984b); suprascripts identify the source of the C-14 dates: 1=GSC 1082, 2=GSC 1221, 3= Karrow (1984b), 4=GSC 271, 5=GSC 534.

lies above the Sunnybrook, range from 38.9 to >53 ka, and C-14 ages for the Scarborough Formation, which lies beneath the Sunnybrook, are in excess of 53ka (Lowden et al., 1971; Karrow, 1967; **Table 1.1**). The Scarborough Formation is thought to be a late interglacial/early glacial deposit (>60ka), and is probably too old for C-14 dating techniques; dates from the Lower Thorncliffe Formation are at the limit of reliability for C-14 dating (<30-35 ka) and may be inaccurate due to old carbon error. However, two dates obtained from the Upper Thorncliffe (28.3 and 32.0 ka; Lowden et al., 1971) are sufficient to constrain the Halton Till to Late-Wisconsin time.

Other techniques that have been used to establish a chronology of events at the Scarborough Bluffs include interregional lithostratigraphic correlation (Dreimanis, 1977; Karrow, 1984b) and thermoluminescence (TL) dating (Berger, 1984; Berger and Eyles, 1994). Each of these techniques will be discussed below.

Lithostratigraphic correlation

Figure 1.3 shows the till chronology for Upper St. Lawrence, Lake Ontario and Lake Erie basins established by Dreimanis (1977). Dreimanis (1977 and references therein) identified a series of stadials and interstadials within the Scarborough sequence during the Wisconsin glaciation based on lithostratigraphic correlations and radiocarbon dates. In his interpretations, the Sunnybrook is deposited during the Guildwood Stadial and is correlated with the Gentilly Till (St. Lawrence Lowlands) and the Upper Bradtville Till (Lake Erie Basin). Work completed since this analysis suggests that simple lithological correlation does not allow for complex facies changes in glacial and ice marginal environments (Eyles, N. et al., 1983), particularly in large lake basins (Eyles and Eyles, 1983). Thus, correlations of outcrops on the basis of lithology alone are not justifiable.

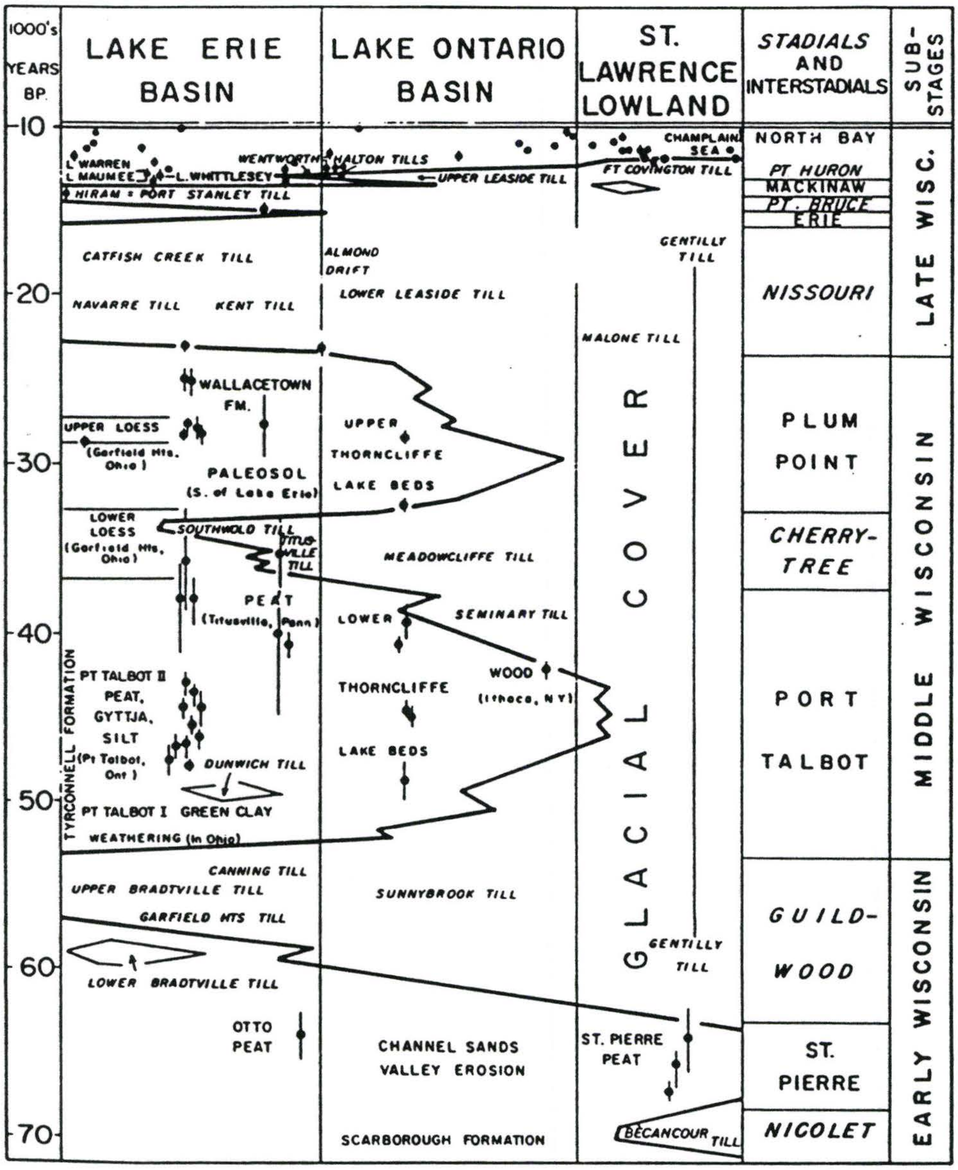


Figure 1.3: Till chronologies from Dreimanis (1977). Glacial deposits are shown by slanted letters; nonglacial events, deposits and lake phases by vertical letters. Radiocarbon dates (with standard deviations) are shown by black dots and heavy lines indicate the glacial margin.

Thermoluminescence (TL) dating

A recently developed dating technique - thermoluminescence (TL) dating - has also been applied to the Bluffs' stratigraphy. TL methods have great potential for dating sediments deposited in the last million years, provided that a number of problems can be addressed (Wintle and Huntley, 1982). Thermoluminescence is the name given to the light emitted by a material when it is heated, after having been previously exposed to ionizing radiation (i.e. exposure to sunlight; Wintle and Huntley, 1982). Because of the sensitivity of some minerals to ionizing radiation, the amount of time since those minerals were last exposed to light can be determined, which is presumed to correspond to when the sediments were deposited. The age of the deposit can be determined using TL methods given that both the sensitivity of the material and the radioactivity of the post-depositional environment are known - postdepositional bombardment of sediments by ionizing radiation (e.g. exposure to light or heat) will affect the final TL signal and may produce under-estimates of age.

This dating method relies on the assumption that the ionization energy 'count' was 'set to zero' at the time of deposition. Heating of the materials/sediments at the time of deposition can 'zero' sediments (e.g. TL dating of pottery fragments has been very successful because of the kilning process; Wintle and Huntley, 1982); however, zeroing of unheated grains of quartz and feldspar, in some sedimentary environments, is incomplete and may produce dating errors (Berger and Easterbrook, 1993). Sediments in ice-proximal lacustrine (Berger and Easterbrook, 1993) and subglacial environments (Berger and Eyles, 1994) have been shown to yield over-estimates many times the expected ages. Over-estimates are expected in these environments because of the absence of zeroing mechanisms (e.g. these sediments are deposited in dark, cool, and murky environments).

TL-dates pertinent to the Scarborough Bluffs are summarized in Berger (1984) and Berger and Eyles (1994; **Table 1.1**). An initial date of 66±7 ka for the Sunnybrook (Berger, 1984) agrees with an early mid-Wisconsin interpretation (Karrow, 1967; Dreimanis, 1977), and coincides with a peak in the marine $\delta^{18}O$ signal (isotope stages 4-5: **Fig. 1.4**). Peaks in the marine $\delta^{18}O$ signal indicate expanded ice sheets on the continents (Shackleton, 1987; Miller and de Vernal, 1992). However, more recent TL dating of the Sunnybrook gives an age range of 41-46±9 ka (Berger and Eyles, 1994) which is younger than some of the existing radiocarbon dates for the overlying Lower Thorncliffe Formation (38-53ka; **Table 1.1**) although these dates may be unreliable. Early estimates of a TL date for the Sunnybrook (66±7 ka: Berger, 1984) are likely over-estimates due to the use of high-energy optical bleaching (Clark et al., 1993). Recent research (Berger and Easterbrook, 1993, and references therein) continues to stress the uncertainty associated with the zeroing process.

In summary, dating control for the Sunnybrook is still inadequate. C-14 dates for the Lower Thorncliffe Formation contain old carbon errors and are too old (>40 ka) to be reliable for confident interpretations. If the non-infinite C-14

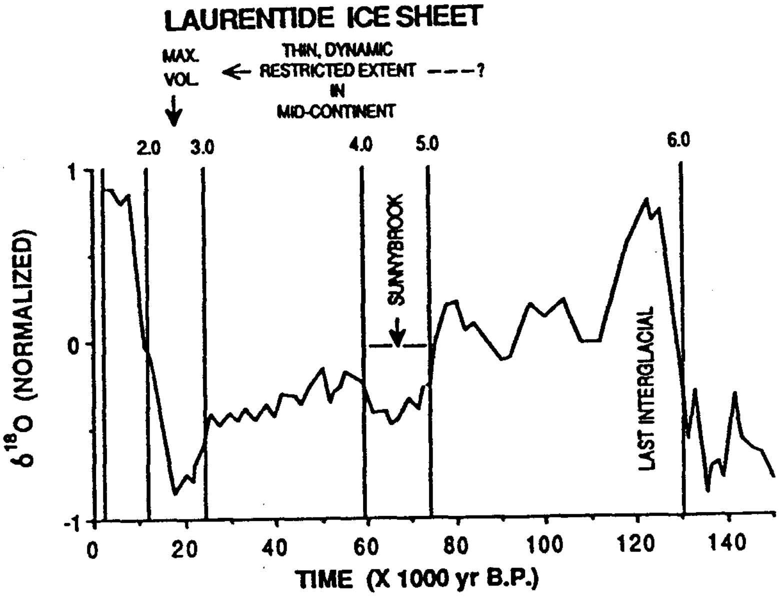


Figure 1.4: High-resolution chronostratigraphy of marine $^{18}O/^{16}O$ changes recorded by benthic foraminifera (from Martinson et al., 1987) and behaviour of Laurentide Ice Sheet suggested by Eyles and Westgate (1987). Vertical lines indicate oxygen-isotope stages; arrow shows TL date on Sunnybrook diamict, obtained by Berger (1984), with error bars. Source: Eyles and Westgate (1987).

dates for Lower Thorncliffe are accepted (38.9 to 48.8 ka), it is possible that either the 41-46 ka or the 66 ka TL date for the underlying Sunnybrook is reasonable.

1.3 DEPOSITIONAL HISTORY OF THE SCARBOROUGH SUCCESSION

Early interpretations of the glacial succession exposed at the Scarborough Bluffs were concerned with identifying evidence for ice advances into the Lake Ontario basin during the Wisconsin (Hinde, 1877; Coleman, 1932; Dreimanis and Terasmae, 1958; Karrow, 1967; **Fig. 1.5**). Diamicts within the succession (Sunnybrook, Seminary, Meadowcliffe and Halton; **Fig. 1.2**) were interpreted as tills recording subglacial conditions; these are interfingered with sands interpreted as glaciolacustrine deposits (Thorncliffe Formation; **Fig. 1.2**) and suggested the formation of high-level proglacial lakes following each ice sheet recession. Recent interpretations of the stratigraphic succession propose glaciolacustrine conditions for the formation of the Sunnybrook, Seminary and Meadowcliffe diamicts, suggesting continuous lacustrine conditions throughout the early and mid- Wisconsin with restricted ice volumes in the basin (Eyles and Eyles, 1983; **Fig. 1.6**).

The oldest sediment unit preserved in Toronto's Pleistocene stratigraphy is the **YORK TILL**, presumably deposited during the Illinoian glacial period (>130ka; Karrow, 1967). It is poorly exposed but is known to rest uncomformably on the regional bedrock - the Georgian Bay Formation

Figure 1.5: Early Interpretations of the Scarborough Succession:

These figures show a plan view of lake and ice sheet position (left box) and a cross-section of simultaneous changes to the Quaternary stratigraphy at the Scarborough Bluffs (right box). Modern lake level is $\approx$75m.a.s.l., just above the Don Formation. **a)** Glacial Lake Scarborough. A stationary ice front blocking St. Lawrence drainage and the Scarborough delta (coarsening upwards sequence) is deposited at the mouth of the Laurentian channel near Toronto (A) in a high level lake. Lake is drained via the Rome outlet (B) to the Hudson River system. **b)** The ice margin has retreated several 100 km north returning drainage to St. Lawrence system (A). Lowered base level and lake level due to isostatic depression of the outlet causes exaggerated dissection of channels into the Scarborough delta (B). Sporadic gravel deposits in the channels are the remnants of this subaerial fluvial interval (C). **c)** Ice advanced over the Scarborough area covering a proglacial outwash deposit in the Guild Inn channel (A) with the Sunnybrook Till. The Sunnybrook drape is thickest in the channels. **d)** Partial retreat of the ice sheet leaves the Rome outlet blocked; high level lake ($>>$122 m.a.s.l.) drains southward to Ohio and Mississippi Rivers (A). Laminated sediments are deposited as channel fills requiring stationary ice margin for several hundreds of years (Antevs, 1928 counted 1200 varves). **e)** Drainage down the Laurentian channel is re-established and the Lower Thorncliffe delta progrades across the sequence into a high level lake ($\approx$130-140 m.a.s.l.). In subsequent Thorncliffe deposits (Middle and Upper), lake levels were higher ($\approx$ 150-175 m.a.s.l.).

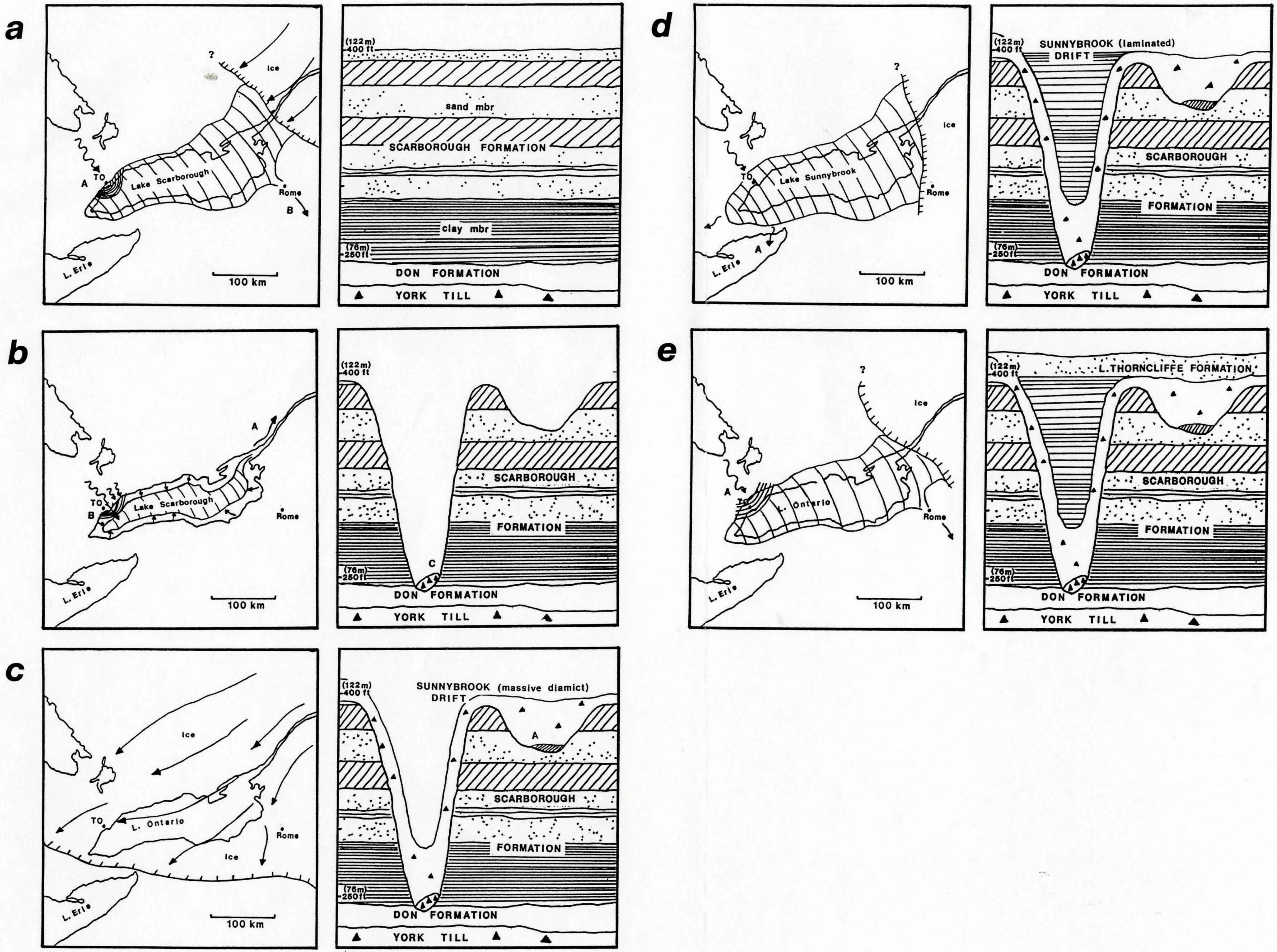

a
?
ice
A
TO
Lake Scarborough
Rome
B
L. Erie
100 km
(122m) 400 ft
sand mbr
SCARBOROUGH FORMATION
clay mbr
(76m) 250 ft
DON FORMATION
YORK TILL
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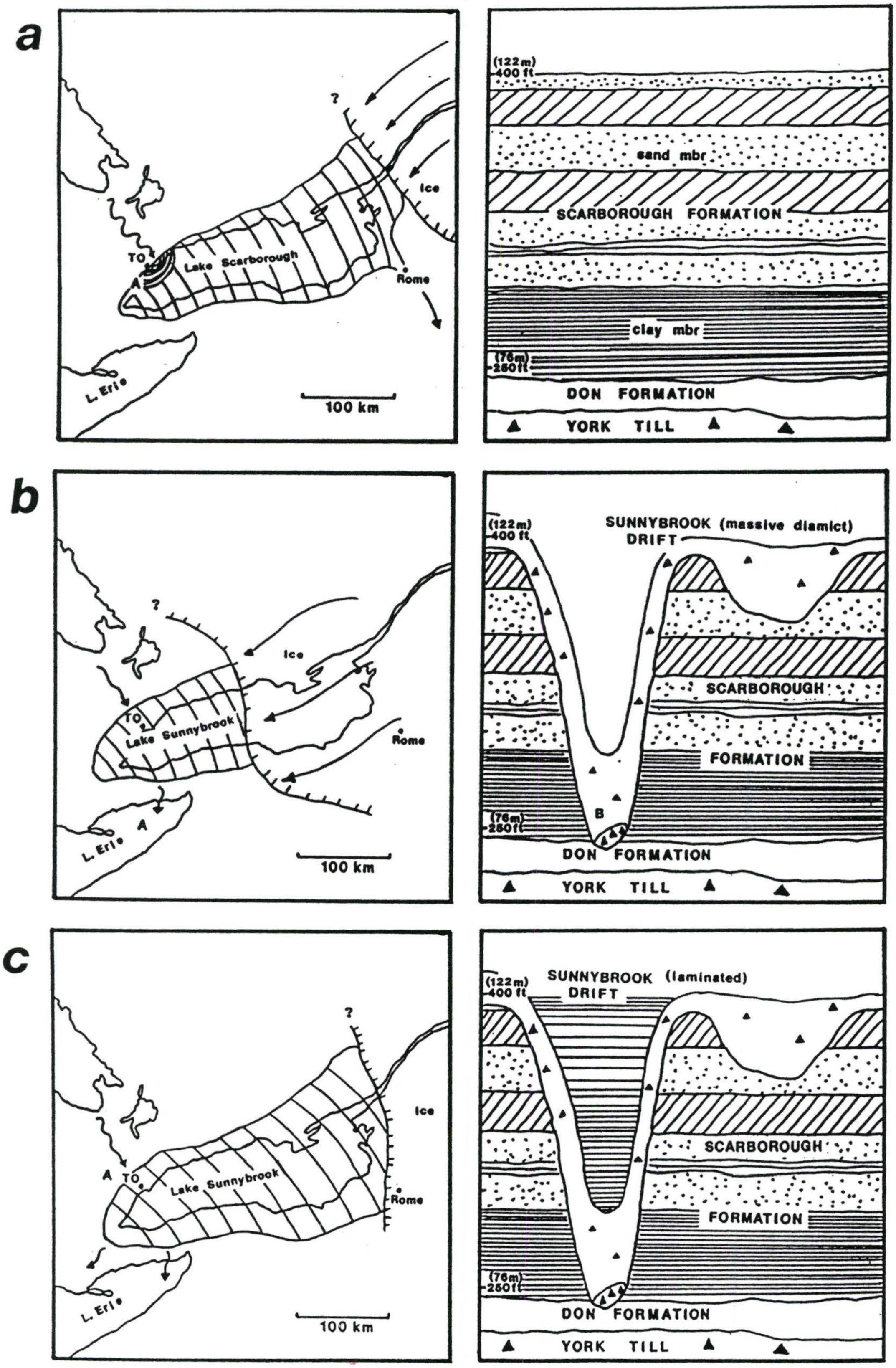
Figure 1.6: Recent Interpretations of the Scarborough Succession: a) Glacial lake Scarborough formed when the St. Lawrence outlet was blocked by ice. A classic coarsening upwards delta is deposited at Toronto (A) (similar Fig. 1.5a). **b)** Eyles argues for continuous presence of a lake at Scarborough during early and mid-Wisconsin. Large channels in the top of the Scarborough Formation formed subaqueously; drainage of high level lakes was south to Ohio and Mississippi basins (A). The Sunnybrook diamict was deposited by a combination of rain-out from icebergs and resedimentation of accumulating pebbly-muds to topographic lows. Input of sediments from streams north and east of Toronto would have continued. No comment was made by Eyles (1982) on the fluvial remnants in the base of channels (B). **c)** In late Sunnybrook time, the influence of ice lessened. Only fine-grained material was deposited (little ice rafted debris), with a sequence of fine-grained turbidites infilling the channels. The Sunnybrook's laminated facies grade into the Lower Thorncliffe sands as the delta progrades into the lake (A).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(Ordovician). Warm climatic conditions during the last interglacial (Sangamon ≈125 years B.P.) are recorded in the **DON FORMATION**, exposed in the Don Valley Brickyard, with climatic conditions interpreted to be 5°C warmer than present (Terasmae, 1960; Williams et al., 1981). The onset of cooling conditions at the beginning of the Wisconsin is recorded by the **SCARBOROUGH FORMATION**, when climatic conditions were 10°C cooler than present ("boreal" climates: Terasmae, 1960; Morgan and Morgan, 1976).

The Scarborough Formation is interpreted as an ancient delta formed where a large southwardly flowing river entered a large lake, Glacial Lake Scarborough (Karrow, 1967) which had a level approximately 46m above present lake level (**Fig. 1.5a**). The outlet for Glacial Lake Scarborough is assumed to be at Rome, New York, rather than through the St. Lawrence Valley, which was blocked by ice at this time (Karrow, 1967: **Figs. 1.5a** and **1.6a**). The location of the large river was governed by the large bedrock channel it occupied (i.e. part of the Laurentian channel: Eyles, N. et al., 1985). Deltaic sediments of the Scarborough Formation form a classical coarsening upwards sequence, beginning with a clay member (≈28m thick) composed of interbedded clays, silts, and fine sands and passing upwards into a sand member (≈15m thick) composed predominantly of cross-bedded and ripple cross-laminated sands indicating southward directed palaeocurrents (Karrow, 1967; Clark, 1986).

Several large channels (up to 53m deep) dissect the upper surface of the Scarborough Formation along the Bluffs; the formation of these channels, however, is poorly understood. Proposed origins include: subaerial downcutting through the delta by a drop in regional base level (i.e. lowered lake levels; Karrow, 1967; **Fig. 1.5b**), and subaqueous dissection by the delta's distributary channels (Eyles and Eyles, 1983; **Fig. 1.6b**). The latter interpretation is based on the lack of evidence supporting subaerial exposure (e.g. weathering, fluvial remnants) and sedimentological interpretations of persistent high lake levels in the Ontario basin during the Wisconsin.

Three interpretations have been proposed to explain the depositional origin of the **SUNNYBROOK**, each with different implications for the interpretation of the magnitude and frequency of ice sheet fluctuations during the Wisconsin. Karrow (1967) and Dreimanis (1977) used clast and matrix provenance of the Sunnybrook and regional lithological correlations to infer ice coming onshore at the Bluffs and depositing the Sunnybrook as a subglacial till (**Fig. 1.5c**). Ice withdrawal from the Ontario basin and subsequent development of an ice proximal lake led to the infilling of topographic lows with laminated sediments (**Fig. 1.5d**), which were initially described as varves (Antevs, 1928; Coleman, 1932; Karrow, 1967; Lajtai, 1967). The second interpretation for the Sunnybrook is based on sedimentological analysis of the Sunnybrook, Seminary and Meadowcliffe diamicts and proposes a glaciolacustrine origin for these units (Eyles and Eyles, 1983). The glaciolacustrine model emphasizes the role of rain-out sediment from suspension and ablating icebergs as a mechanism for the production of pebbly lake bottom muds or massive diamict units (**Fig. 1.6b**).

Reduction of glacial influence and initiation of subaqueous slumping and turbidity current activity produced the 'laminated' Sunnybrook unit (**Fig. 1.6c**). The most recent interpretation of the Sunnybrook suggests the operation of both subglacial lodgement and deformation till processes during deposition (Hicock and Dreimanis, 1989; 1992a). Ice sheet positions and lake levels, in this last model, are similar to those of Karrow (1967). Each of these three interpretations of the Sunnybrook will be discussed in detail in section 1.4.

The **THORNCLIFFE FORMATION** is dominantly sandy and is divided into Upper, Middle, and Lower Thorncliffe Members which are separated by two diamict units, the **SEMINARY** and **MEADOWCLIFFE** diamicts. The two diamicts have limited exposure in the central Bluffs (**Fig. 1.2**) and are not found in any of the creek exposures. Sands of the Thorncliffe Formation were deposited by an extensive delta entering a large high level lake (at least 40m above present lake level; Karrow, 1967; Clark, 1986; **Fig. 1.5e**). The two diamicts were formed in an environment similar to that of the Sunnybrook, either subglacial (Karrow, 1967) or subaqueous (Eyles and Eyles, 1983).

The Laurentide ice sheet reached its maximum extent during the Late Wisconsin in eastern North America (Clark et al., 1993) and deposited extensive subglacial till sheets such as the Leaside Till (Karrow, 1967) and Halton Tills (Karrow, 1984b) in southern Ontario. Considerable geomorphological evidence, such as drumlin fields which lie to the north and east of Toronto (Boyce, 1990) support a subglacial origin for these surficial deposits. It is believed that the

Halton event removed much of the stratigraphy at the eastern and western margins of the Bluffs **(Fig. 1.2)**, primarily by erosion and basal incorporation of material into a subglacial deforming bed (Boyce and Eyles, 1991). The Halton Till is thought to have been deposited by a combination of deformation and lodgement processes (Boyce and Eyles, 1991).

Following the retreat of Late Wisconsin ice a series of post-glacial lakes occupied the Lake Ontario basin. The largest of these was **LAKE IROQUOIS** (Main Iroquois at ≈11,500 years B.P.; Sly and Prior, 1984), with water levels approximately 50m above modern lake level. Lake Iroquois eroded extensive shoreline features along the northern shore of Lake Ontario and removed much of the post-Sunnybrook stratigraphy at the Scarborough Bluffs; a small 'island' in the central Bluffs region contains the complete interglacial-glacial succession **(Fig. 1.2)**.

In summary, the Scarborough stratigraphy is dominated by alternations of deltaic sands (Scarborough and Thorncliffe formations) with diamicts (Sunnybrook, Seminary, Meadowcliffe, and Halton). Subglacial interpretations for the diamict units (Karrow, 1967; Hicock and Dreimanis, 1992a) imply a dynamic margin of the Laurentide ice sheet within the Lake Ontario basin during the Wisconsin, with ice sheet margin fluctuations on the order of several 100's of kilometres **(Fig. 1.5)**, whereas glaciolacustrine interpretations (Eyles and Eyles, 1983) imply prolonged high lake levels and restricted ice extent until late Wisconsin.

1.4 PREVIOUS WORK ON THE SUNNYBROOK

Previous work on the Sunnybrook has proposed three types of environmental interpretation: 1) grounded ice, 2) glaciolacustrine, and 3) subglacial/deformation till interpretations.

1.4.1 EARLY GROUNDED-ICE INTERPRETATIONS

In the 1950's and 1960's, the only models available for interpretation of poorly-sorted (till-like) glacigenic deposits were grounded ice models (e.g. Boulton, 1971) which suggested an origin as tills by subglacial deposition. Early work at Scarborough Bluffs interpreted the Sunnybrook and other fine-grained diamicts as till (Dreimanis and Terasmae, 1958; Karrow, 1967). Karrow (1967) proposed a model for the mid-Wisconsin interval at Scarborough in which Laurentide ice advanced over the Metro Toronto area several times, displacing large lakes. Diamict units (e.g. Sunnybrook, Seminary, Meadowcliffe, Halton) were deposited during periods of ice sheet advance and sand units (e.g. Thorncliffe) were deposited during periods of rapid delta progradation into deep lakes.

Early studies concentrated on documenting and interpreting the physical properties of Sunnybrook 'till' (Lajtai, 1966; 1969; Karrow, 1967) in order to make interregional correlations and reconstruct ice flow directions. Documented attributes of the Sunnybrook include matrix composition (e.g. carbonate content) and analysis of the clast component (**Tables 1.2** and **1.3** respectively). Carbonate studies established an unique signature for the Sunnybrook matrix - the Calcite-to-Dolomite ratio (CDR = 0.9-1.5) - which has been used as a means of correlating the Sunnybrook in outcrops across Metro Toronto and at the Bowmanville Bluffs

"Till" Unit	Calcite Percent	Dolomite Percent	CDR[3]
Lajtai Sunnybrook[1] 1969 St. George[1]	8 (42) 23 (14)	5.5 (42) 7.0 (14)	1.5 (42) 3.3 (14)
Lajtai Lansdowne[1] 1966 Pape[1]	21 (20) 22 (6)	7.0 (20) 7.0 (6)	3.0 (20) 3.1 (6)
Sunnybrook[2] Karrow Seminary[2] 1967 Meadowcliffe[2] Leaside[2]	6 (22) 18 (8) 24 (9) 25 (26)	6.5 (22) 7 (8) 6 (9) 6 (26)	0.9 (22) 2.7 (8) 4.1 (9) 4.0 (26)
Brookfield Port Hope[2] et al.,1982	9.9 (3)	6.6 (3)	1.3 (3)

Table 1.2: Carbonate analyses of matrix within Wisconsin 'tills' of the Toronto (Lajtai, 1966; 1969 and Karrow, 1967) and Bowmanville (Brookfield et al., 1982) areas. Notes: 1=median values, 2=average values, 3=Calcite-to-Dolomite Ratio; bracketed values are the number of analyses.

Site # (Karrow)	Limestone (%)	Dolomite (%)	Shale (%)	Sandstone (%)	PreCamb. (%)
A1001	51	5	38	1	5
A1005B	61	3	33	0	2
A1006	25	1	66	0	6
A1009D	40	2	40	0	18
A1010C	48	26	1	12	12
A1011D	33	35	0	0	32
A1013B	41	24	0	0	35
A1017	12	20	0	47	19
A1019	31	17	42	1	8
A1020D	51	20	0	0	29
A1022	55	7	35	0	3
A1023	49	10	28	3	10
AVERAGE	41	14	24	5	15
H&D 1989	43	28	<1	15	14(other)

Table 1.3: Clast lithologies for the Sunnybrook diamict, compiled by Karrow (1967) and Hicock and Dreimanis (1989; Table 1) to infer clast provenance, for sites along the Bluffs. Data suggest strong influence of regional bedrock outcrops of limestone, dolomite and shale.

(**Table 1.2**; Brookfield et al., 1982). Clast lithologies are utilized to infer provenance for the materials. The Sunnybrook contains predominantly limestone, dolomite and shale clasts (Karrow, 1967; **Table 1.3**), although Hicock and Dreimanis (1989) report only a small percentage of shale. These clasts were probably derived from outcrops in eastern Ontario, near Ottawa and Kingston (Dreimanis and Terasmae, 1958; Karrow, 1967), although they may have been reworked from earlier deposits.

Analysis of physical properties alone such as carbonate analysis and clast provenance, **cannot** provide data regarding sediment genesis and only have limited importance in modern studies of sediment provenance. It is now realized that much glacial sediment is polycyclic (reworked from older glacial deposits) which makes provenance signatures unclear. The early studies on the Sunnybrook (Dreimanis and Terasmae, 1958; Karrow, 1967) focused on the interregional correlation, not on the origin of the sediments. Correlations were based on lithological properties rather than using environmental parameters established in later studies. As a result, the complexity of the Sunnybrook's depositional environment was not realized in early studies.

1.4.2 GLACIOLACUSTRINE INTERPRETATIONS

Greater understanding of glaciomarine and glaciolacustrine depositional environments that developed in the 1970 and 1980's (May, 1977; Orheim and Elverhoi, 1981; Powell, 1981; Molnia, 1983) led to new interpretations for glacigenic sequences previously interpreted as tills, including those at

Scarborough (Eyles and Eyles, 1983). Based on the first sedimentological descriptions of the Sunnybrook, Seminary, and Meadowcliffe diamicts at Scarborough, Eyles and Eyles (1983) proposed that glaciolacustrine conditions existed at Scarborough through the whole of the early- and mid- Wisconsin. The non-genetic term 'diamict' was introduced to describe the poorly-sorted deposits previously referred to as 'tills'. Diamicts were thought to have been deposited in a large ice contact lake by a combination of 'rain-out' of sediment from suspension and ablating icebergs, and resedimentation of lake bottom sediments into topographic lows (Eyles and Eyles, 1983). During periods of ice margin recession and/or water level drop, the influence of ice decreased and deltaic deposits (e.g. Thorncliffe Formation) were deposited over individual diamicts.

The main lines of evidence in support of glaciolacustrine depositional conditions for the Sunnybrook, cited by Eyles and Eyles (1983) are: **(1)** the identification of conformable and interbedded contacts with the underlying deltaic Scarborough Formation, **(2)** the absence of erosional basal contacts (commonly described in subglacial models) and evidence of subaerial weathering of the top of the Scarborough Formation, and **(3)** the presence of loading along the contact between Thorncliffe sands and the uppermost Sunnybrook diamict which suggested the diamict was highly water saturated at the time of sand emplacement. Their sedimentological descriptions identified structures which could only be formed in subaquatic environments, including flow noses and silt clast breccia within massive diamict units. The introduction of a new, glaciolacustrine interpretation, for the Sunnybrook, Seminary and Meadowcliffe diamicts, initiated a vigorous debate which has continued to the present day (Hicock and Dreimanis, 1992a, and references therein).

Recently, the glaciolacustrine model has been strengthened by the identification of intact ostracods within massive diamict facies (**Fig. 1.7**; Westgate et al, 1987; Rutka and Eyles, 1989; Schwarcz and Eyles, 1991). The species of ostracods found (*Candona candata*, *Candona subtriangulata*, and *Darwinula stevensoni*) have specific water depth and temperature tolerances (**Table 1.4**) and can be used to infer lake conditions at the time of deposition. A glaciolacustrine depositional environment assumes that the sediments are "in situ" (i.e. have not been re-worked since their deposition).

Ostracod Species	depth range	mean depth	temperature range	mean temp.	d.f.s.	mean d.f.s.
C.caudata	0.2-287m	32m	3.4-27°C	12°C	0-62km	3km
C.subtriangulata	8-365m	140m	2.6-19.2°C	5.4°C	0.2-63km	20km
D.stevensoni	0.1-16m	2.3m	9-33.4°C	21.4°C	0-21km	0.3km

Table 1.4: Depth and temperature tolerances for *Candona species* and *D.stevensoni* for data collected from Scarborough Bluffs. Data summarized from Westgate et al. (1987); distance from shore ("d.f.s."), is determined from modern analogues.

Both Candona species are present throughout the Sunnybrook diamict, but D.stevensoni (recording the shallowest lake depths) is restricted to the uppermost diamict facies (sample f; **Fig. 1.7**). Ostracod valves are present in both intact and fragmented forms (30% intact; 20% minor damage; 50% fragments; **Fig. 1.7**); intact ostracod valves within the Sunnybrook are used to infer subaquatic

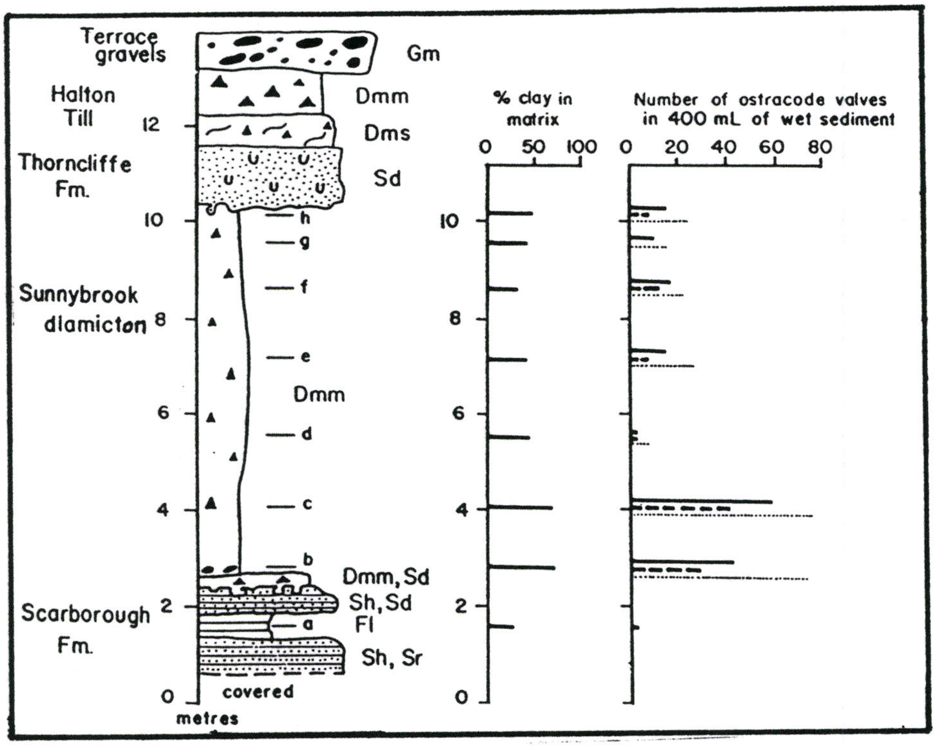


Figure 1.7: Various degrees of ostracod preservation in the Sunnybrook diamict at Rouge River site (from Westgate et al., 1987). Heavy solid line = whole (intact) valves (30%); heavy dashed line = valves with only minor damage (20%); dotted line = small fragments of valves(50%).

depositional conditions (Westgate et al., 1987; Rutka and Eyles, 1989). Lake conditions during deposition of most of the Sunnybrook would have been comparatively cool and deep (5.4-12°C; 32-140m; **Table 1.4**). A greater occurrence of ostracods in the base of the diamict (recorded on **Fig. 1.7**) suggests conditions more favourable for lacustrine fauna early in the depositional interval (Westgate et al., 1987). The occurrence of D.stevensoni in the upper Sunnybrook indicates a warmer and shallower lake <u>only</u> at the end of the Sunnybrook interval (21.4°C; 2.3m).

Based on depth and temperature preferences of ostracod species present (**Table 1.4**), a decrease in ostracod abundance would suggest a decrease in depth and/or a decrease in temperature of the lake during deposition. However, the observed decrease in ostracod numbers is not gradual but stepped (e.g. at ≈4m on vertical scale; **Fig. 1.7**). A step change in ostracod content may infer rapid lake level changes during Sunnybrook time.

Oxygen isotope ratios ($\delta^{18}O = {}^{18}O/{}^{16}O$), measured from ostracods found in the Sunnybrook and related diamicts, have also been used to establish a chronological and climatic framework for the Bluffs succession (Schwarcz and Eyles, 1991). The growth and decay of ice sheets is related to $\delta^{18}O$ ratios within marine sediments (Miller and de Vernal, 1992; **Fig. 1.4**). Ostracods precipitate a calcite valve in near "oxygen isotopic equilibrium" with the water in which they grow (Rutka and Eyles, 1989). Hence, oxygen isotope data should provide information regarding both the $\delta^{18}O$ of lake water and the water temperature at the time of formation of ostracods (Schwarcz and Eyles, 1991). Conditions affecting deposition are:

[1] If water temperature remains constant, similar $\delta^{18}O$ values should exist between calcite of ostracods and the lake water they inhabit.
[2] If $\delta^{18}O$ of water is kept constant, then $\delta^{18}O$ of calcite decreases approximately 0.25 parts per thousand (ppt) for each degree increase in temperature.

At the Bluffs, Schwarcz and Eyles (1991) have shown the decrease in the $\delta^{18}O$ is approximately 10 p.p.t. moving upwards from the Scarborough Formation through to the Meadowcliffe diamict (**Fig. 1.8** and below).

RANGE OF $\delta^{18}O$ (ppt, parts per thousand)	
Scarborough Formation:	-6 to -8 ppt
Sunnybrook:	-8 to -11 ppt
Seminary:	-12.5 to -15.5 ppt
Meadowcliffe:	-12.2 to -17.6 ppt

The decrease in $\delta^{18}O$ corresponds to either a temperature **increase** of nearly **40°C!!** (see point [2] above), or an influx of lower $\delta^{18}O$ water. Other authors have documented a cooling trend moving upwards through the Scarborough succession (Berti, 1975; Williams et al., 1981) and warmer water conditions only at the end of the Sunnybrook interval (Westgate et al., 1987), thus an increase in lake water temperature of 40°C is improbable. The progressively lower $\delta^{18}O$ values measured by Schwarcz and Eyles (1991) more likely suggest an approaching ice margin with abundant meltwaters (rich in ^{16}O) being delivered to the lake in which the Sunnybrook and later diamicts were being deposited.

The ideas proposed by Schwarcz and Eyles (1991) are in agreement with

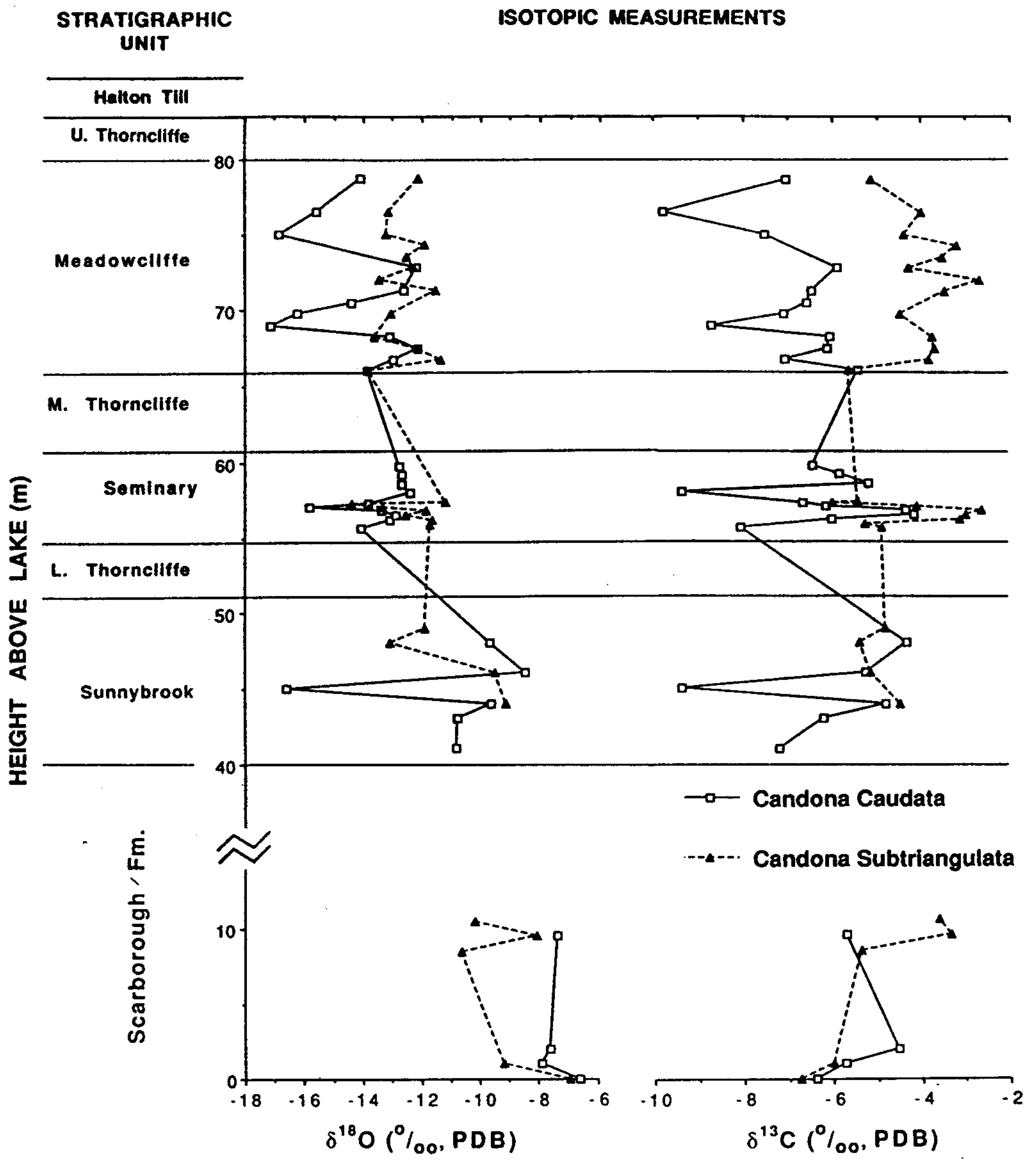


Figure 1.8: Variation in $\delta^{18}O$ and $\delta^{13}C$ for ostracods (Candona species) found at the Sylvan Park section (for Sunnybrook and Scarborough units) and the Hi section (for Seminary and Meadowcliffe units) along the Scarborough Bluffs. Ostracods are not present within the sand facies of the Scarborough Formation. Source: Schwarcz and Eyles (1991).

the glaciolacustrine model for deposition of the Sunnybrook (Eyles and Eyles, 1983). They argue for the in situ deposition of ostracods which may have been locally re-sedimented to topographic lows, and a general cooling trend represented through the mid-Wisconsin at Scarborough Bluffs. This fits with the overall advance of the ice sheets through the Wisconsin period, with maximum ice sheet extent reached during the Late Wisconsin ($\approx$20,000ka B.P.; **Fig. 1.4**).

Queries have been raised about the presence and environmental significance of ostracods within the Sunnybrook (Nielsen, 1988; Hicock and Dreimanis, 1992a). Nielsen (1988) reports on tills he documented in Manitoba which contained intact specimens of lacustrine fauna (e.g. foraminfera), and cautions that "the presence of delicate unbroken microfossils in a diamicton should not be used solely as a criterion for differentiating glaciolacustrine or glacimarine sediments from till deposits". Westgate and Delorme (1988) rebut that the preservation potential of ostracods, which are more delicate than foraminfera, is not high in subglacial environments, especially in those exercising extensive deformation and pervasive shear of subglacial sediments (e.g. deformation and lodgment till models; Hicock and Dreimanis, 1992a; see section 1.4.3.).

1.4.3 LODGEMENT/DEFORMATION TILL INTERPRETATIONS

The third and most recent model proposed for formation of the Sunnybrook diamict is a combined subglacial lodgement / deformation till model (Hicock and Dreimanis, 1989; 1992a). Hicock and Dreimanis (1992a) cite the presence of striated basal clast horizons, transverse pebble and magnetic fabrics, and shear planes within the Sunnybrook as proof of subglacial conditions, and introduce a deformation till model to explain some of these characteristics.

Deformation till models are commonly referred to as "deforming bed models" and propose that large ice lobes move primarily because of pervasive shearing of subglacial sediments rather than from basal sliding at the glacier-bed contact (Boulton and Hindmarsh, 1987; Alley et al., 1987). High pore water pressures are generated in sediments beneath ice sheets by abundant meltwater, which lowers the strength of subglacial sediments. Hence, subglacial sediments are subjected to lateral pervasive shearing forces generated by the moving ice mass (**Fig. 1.9**). Much of the work completed concerning "deforming-bed" models is in the understanding of ice sheet dynamics and bed conditions (Boulton and Hindmarsh, 1987; Brown et al., 1987; Clarke, 1987). However, the sedimentary product of this process - 'deformation till' - is poorly understood for two reasons: 1) few studies have been carried out in present-day deforming-bed situation to determine facies characteristics, and 2) because deforming models incorporate subtill sediments, the range of facies and structures is theoretically large.

Deformation till is characterized by the abundant inclusion of sub-till sediments that would not likely survive shearing onto a rigid substrate as in a lodgement till model (**Fig. 1.9**; Boulton, 1987; Clayton et al., 1989; Hicock et al., 1989; Boyce and Eyles, 1991). In the upper portions of deforming beds,

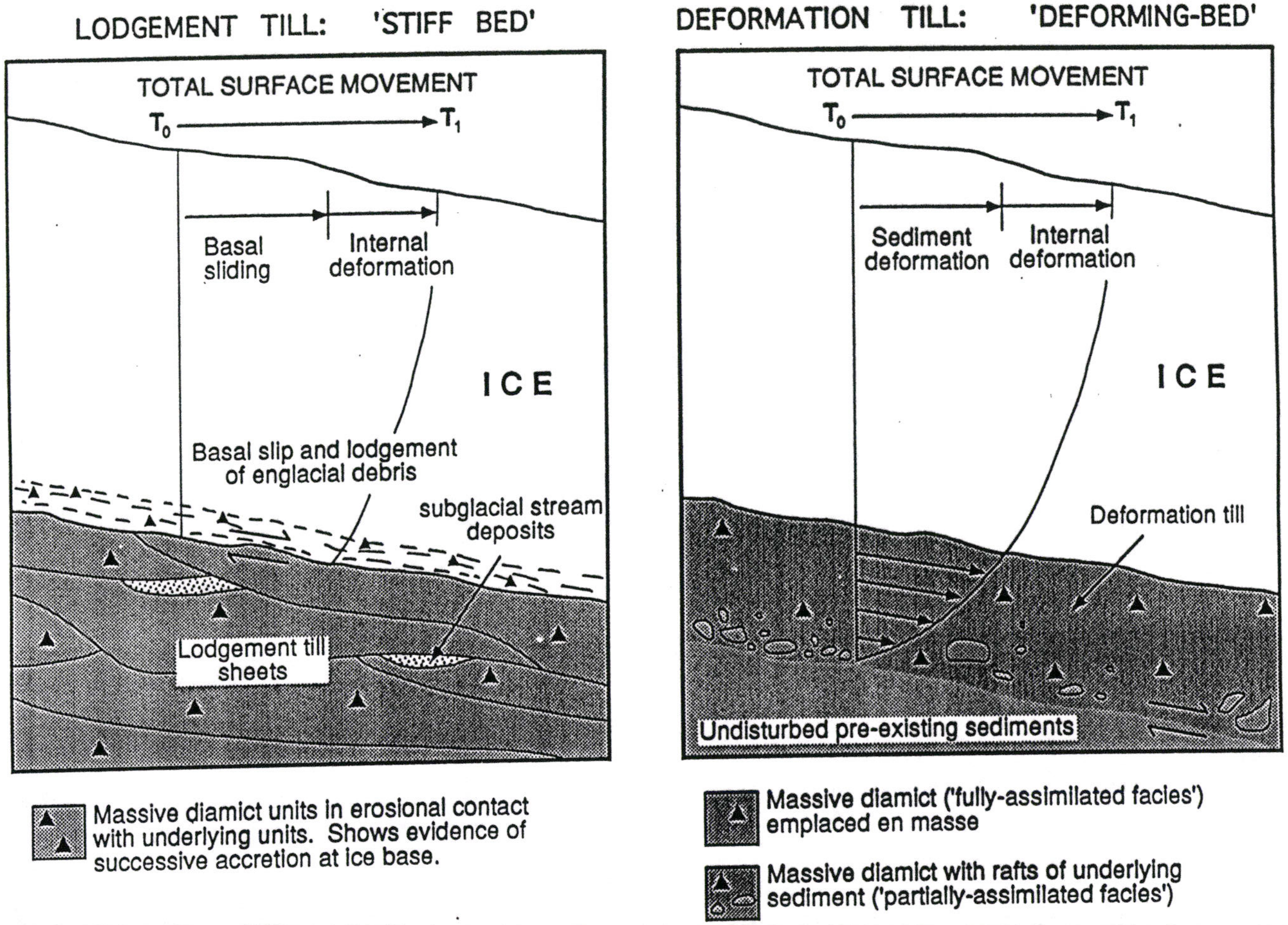


Figure 1.9: Cartoon contrasting the bed conditions for subglacial deposition of lodgement and deformation tills. Lodgement till requires a "stiff", resistant bed while deformation till is the result of pervasive shearing of substrate sediments. Incorporation of substrate sediments, shown on figure, is a diagnostic criteria for the identification of deformation till facies. Sorted sandy units, amongst till facies, representing fluvial intervals, are associated with lodgement till deposits (Eyles, N. et al., 1982). Source: Joe Boyce (pers.comm., 1993).

where more vigourous shearing is implied (Boulton and Jones, 1979), complete destruction of primary structures makes identification of its origin as deformation till difficult if not impossible. Presently available diagnostic characteristics of deformation tills have been compiled from Alley (1991), Boyce and Eyles (1991), Eyles, N. (1993), and Joe Boyce (pers.comm., 1993) and are listed below:

- **presence of glacitectonized substrates**
- **rafts of substrate materials incorporated but not completely admixed**
- **"augen" structures, indicating differential shearing**
- **inclined shear laminations within massive diamict**
- **"injection" structures from underlying unconsolidated sediments**

Hicock and Dreimanis (1992a) suggest that the Sunnybrook is a combination of lodgement and deformation till, citing the character of basal clast horizons as the primary evidence in support of subglacial conditions during deposition of the Sunnybrook diamict.

Striated clast horizons are more commonly reported from lodgement till (Boulton, 1978; Kruger, 1979) than in deformation till facies. In a lodgement till model, clasts are emplaced on the stoss side of obstacles (e.g. other clasts) and produce "clast clusters" (Boulton and Paul, 1976). The mode of formation of striated clast horizons in the deforming bed model is outlined by Clark (1991). Clark (1991) suggests striated clast horizons in deformation till can be explained by a model in which clasts are not held in suspension within a fine-grained subglacially deforming till layer but instead settle to the base of such a layer, becoming lodged into a rigid substrate. Clasts are then abraded by overriding deforming sediment, producing striated tops (Clark, 1991). The ability of a fine-grained deforming mass to produce striated clasts and faceted stones in this way is questioned by Mickelson et al. (1992).

Fabric measurements of clasts within the Sunnybrook's clast horizons - made by Hicock and Dreimanis (1992a) - show moderately strong NE-SW orientations of clast a-axes (**Fig. 1.10**). Hicock and Dreimanis (1992a) use these horizons to confirm a southeasterly flow for the Laurentide Ice Sheet, as suggested by Karrow (1967) based on clast provenance data (section 1.4.1). Magnetic and pebble fabrics in the Sunnybrook diamict, measured by Gravenor and Wong (1987), show a transverse relationship, which is more typical of subaquatic debris flow facies. The use of fabrics in determining genesis of glacigenic deposits is reviewed by Dowdeswell and Sharp (1986) and Rappol (1985); however fabrics produced by deforming bed models are still unclear (Eyles, N., 1993). Fabrics of the Sunnybrook are more characteristic of subaquatic debris flows than of subglacial conditions (Gravenor and Wong, 1987), and therefore have little contribution to subglacial interpretations of the Sunnybrook.

Hicock and Dreimanis (1992a) outline a depositional history for the Sunnybrook. A thin unit of interbedded sand and mud that underlies the Sunnybrook diamict is interpreted as a glaciolacustrine/glaciofluvial unit deposited in a proglacial lake, as ice advanced from the east and northeast in early Sunnybrook time. As ice overrode the Scarborough Bluffs, high pore water pressure in subglacial sediments persisted because of the ice sheet's proximity to a large lake and its abundant subglacial meltwater. Thus, deforming-bed

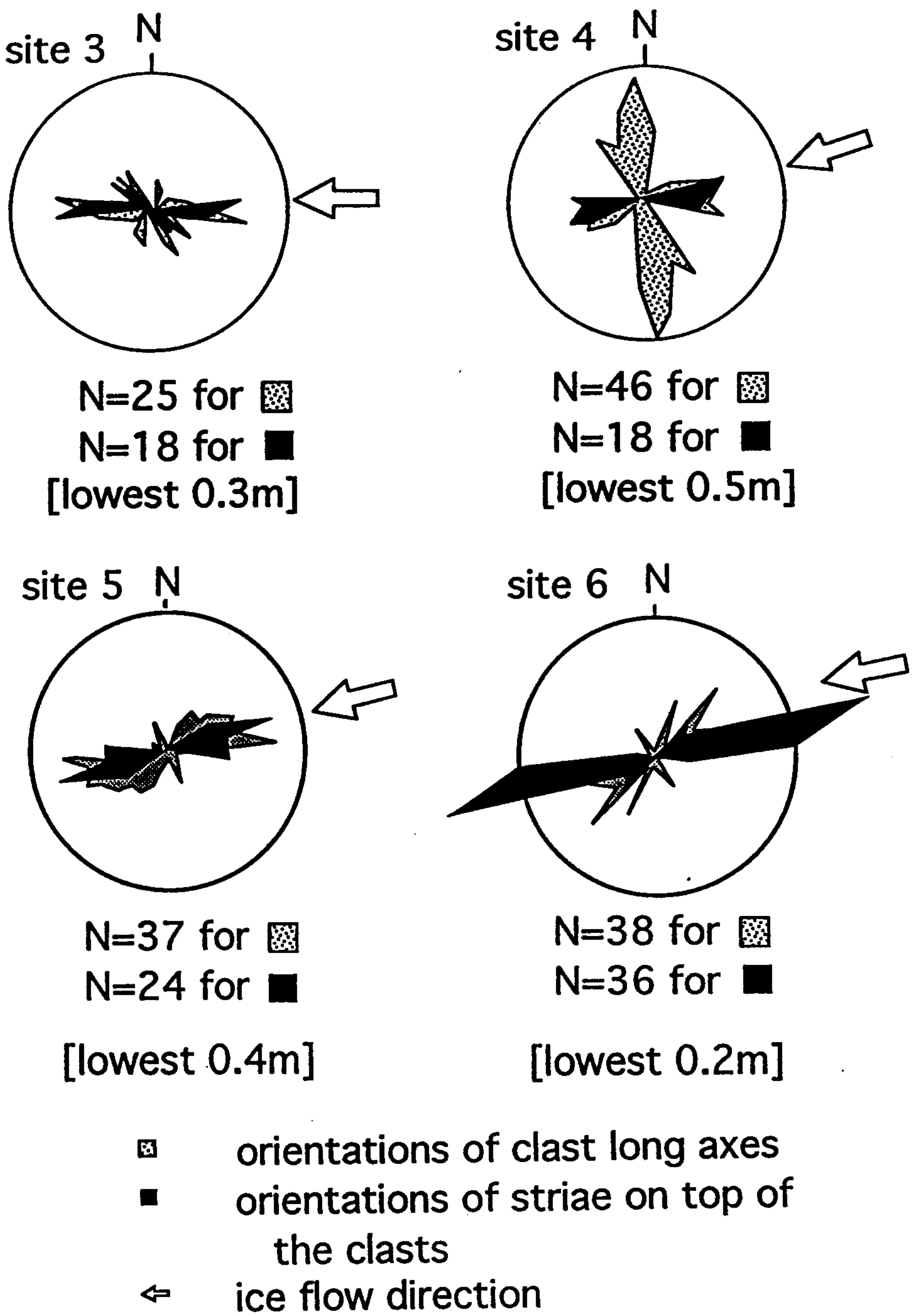


Figure 1.10: Clast orientation data for clast pavements in lower Sunnybrook diamict at Sylvan Park (modified from Hicock and Dreimanis, 1989). Dip measurements are not indicated. Clast horizon data are used by Hicock and Dreimanis (1989; 1992a) to argue a subglacial lodgement/deformation till origin for massive facies within the Sunnybrook, with ice flowing from the NE to the SW.

conditions prevailed. Temporal and spatial fluctuations of pore water pressure in subglacial sediments led to alternating deformation and lodgement till processes across the Bluffs. During lodgement conditions, erosional contacts between the Sunnybrook and underlying sediments developed together with glaciotectonic deformation of the upper Scarborough Formation (Hicock and Dreimanis, 1992a). Clast horizons within the base of the Sunnybrook diamict have origins ascribed to both deformation till (Clark, 1991) and lodgement till processes (Hicock and Dreimanis, 1989; 1992a). Ice recession, following deposition of the Sunnybrook diamict, re-established glaciolacustrine conditions in the basin and allowed the deposition of the laminated unit of the Sunnybrook via turbidity current activity (as described in section 1.4.2 above; Eyles and Eyles, 1983).

There are some outstanding queries with respect to the model of subglacial lodgement / deformation proposed by Hicock and Dreimanis (1992a), most stemming from the present poor understanding of the model's resulting facies. In a process advocating pervasive shearing of subglacial sediments (e.g. lodgement and deforming bed models), it is not clear how fragile ostracod valves could have remained intact. Secondly, almost all of the features included in the list of diagnostic criteria for identifying deformation tills (*p.38*), are **not** identified by Hicock and Dreimanis (1992a) within the Sunnybrook.

Finally, in view of the poor understanding of facies generated by subglacial deforming bed conditions, a thorough review of both the sedimentology and glaciotectonic associations of the Sunnybrook is warranted. The questions raised by Hicock and Dreimanis (1992a) as to the origin of the Sunnybrook and the need for better documentation of the sedimentology of deformation tills gave initial impetus to the present study.

1.5 FIELD AND LABORATORY METHODS

This study focuses on the field documentation of characteristics such as sediment texture, sedimentary structures, the nature of bed contacts, bed geometries, lateral facies variability, clast concentrations and clast fabric. It differs from previous studies in two ways: 1) the Sunnybrook is documented over a much greater area, with 32 logged sections at the Bluffs and in the dissecting creeks, and 2) all available sedimentological, faunal, and glaciotectonic data for the Sunnybrook were collected and/or reviewed. The result of these analyses will be a three-dimensional model describing the Sunnybrook's depositional environment.

1.5.1 FIELD METHODS

The field area is divided into two geographically distinct regions: one is the Scarborough Bluffs, extending from Warden Ave. in the west to Morningside Ave. in the east (**Fig. 1.1**), and the other comprises creeks dissecting the Lake Ontario shoreline north and east of the Bluffs (Highland and Duffins creeks and the Rouge River; **Fig. 1.1**).

The Sunnybrook was logged using standard sedimentological techniques; a lithofacies code (**Fig. 1.11**: Eyles, N. et al., 1983) was used to give shorthand descriptions of sediment types. Logs were taken where outcrops were suitable, generally at intervals of 200m to 1.5km along the Scarborough Bluffs, as well as in the dissecting creeks. It was important to document areas studied by previous researchers to note changes (if any) in the outcrops (e.g Sylvan Park, Dutch Church, Cudia Park, and Hi sections,..; Appendix C), and also those areas where the Sunnybrook displayed significant lateral variability. In the western Bluffs area (west of Bluffers Park, **Fig. 1.2**), many sections were logged through a thinning and discontinuous Sunnybrook unit which had been affected by overriding Late Wisconsin ice during the deposition of the Halton Till. Sections were more widely spaced in the eastern Bluffs area (east of Bluffers Park, **Fig. 1.2**) where there was less variability in Sunnybrook facies and contacts. Some interesting lateral facies variations were present in the Rouge River/Bailey Bridge area (**Fig. 1.1**) and resulted in detailed logging there.

Sites chosen included those of previous workers (Karrow, 1967; Eyles, 1982) and those located during field reconnaissance. A total of 18 sites were logged at the Bluffs and 14 sites at the Rouge River and Duffins creeks; additional descriptions were made of outcrops visited in lower Highland creek (**Fig. 1.1**).

Sedimentological logging focused on the Sunnybrook and units immediately under- and over-lying the Sunnybrook. Up to 2m of the underlying Scarborough Formation and the overlying Thorncliffe Formation were logged, in order to document the nature of contacts with the Sunnybrook and any associated

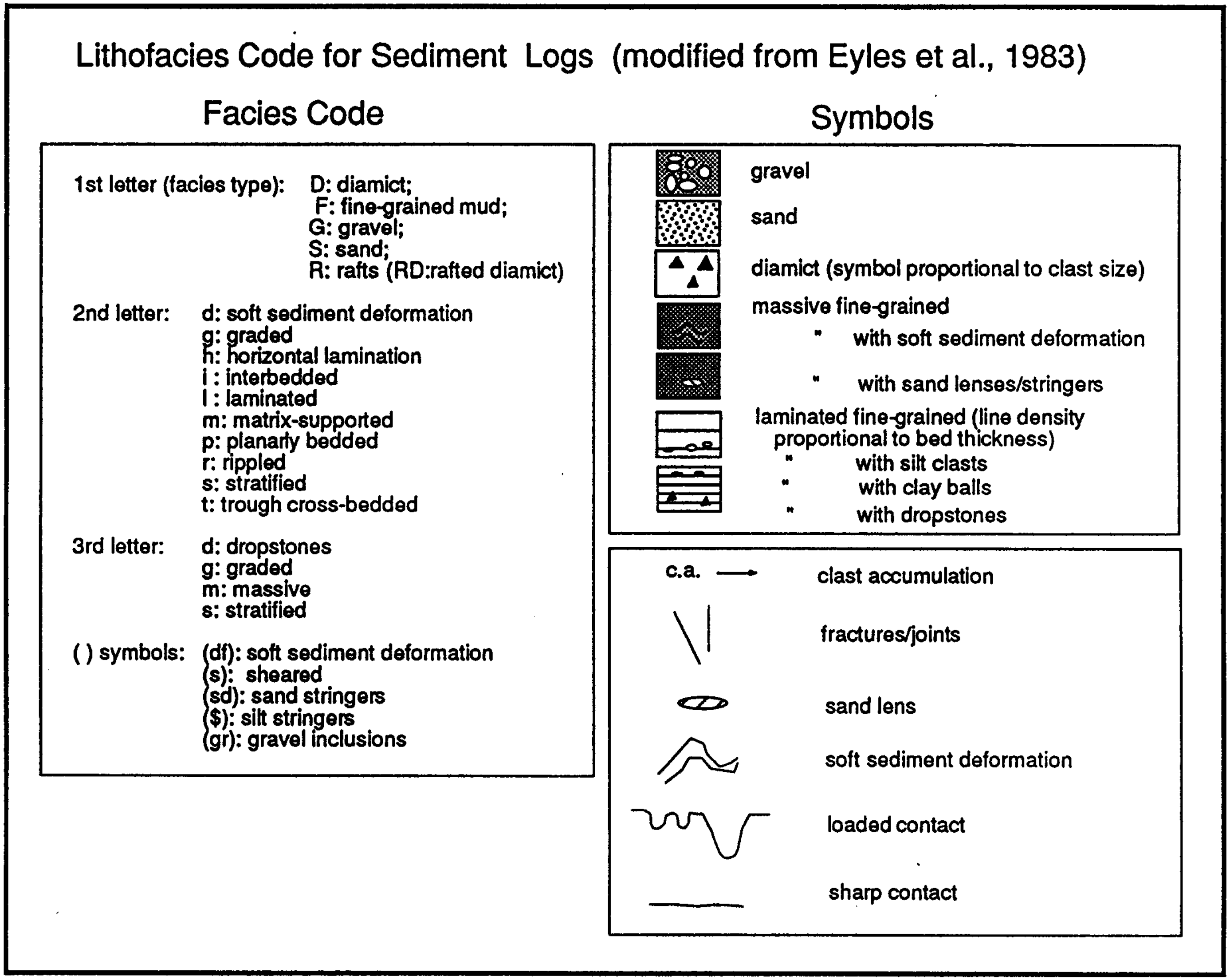


Figure 1.11: Lithofacies code for sediment logging, modified from Eyles, N. et al. (1983). Second and third letters are observed sedimentary structures and grain-size characteristics unique to this study. Examples: Flg(df) = a laminated and graded fine-grained mud which has undergone soft sediment deformation; Dm(sd) = a massive diamict with sand stringers.

deformation features. Logging techniques followed a standard procedure. Weathered or slope wash material was removed from the face by digging and "steps" were cut to provide a continuous vertical profile through the sediment. Sections were logged from top to bottom. Sediments were cleaned with a knife to reveal any structural detail; grain size was noted in the field and samples were collected for later detailed textural analysis. Additional information regarding sedimentary structures, soft sediment deformation, and the nature of contacts between units, were recorded in field notes with appropriate sketches. Field logs were later re-drafted using a Macintosh software package (Canvas v.3.0) at University of Toronto, Scarborough (Appendix A).

Clast fabrics were measured for clasts within basal clast horizons in the lower diamict, noting the length of clast axes, principal (a) axis orientation and dip, and clast shape and markings (Appendix D). Particular attention was paid to the description of these clast horizons as these were used by Hicock and Dreimanis (1989; 1992a) to infer subglacial conditions for the Sunnybrook during its deposition as a deformation till (Clark, 1991).

Determination of the elevation of the lower contact of the Sunnybrook required the use of a Wallace and Tiernan surveying altimeter. Measurements were completed in 3 closure loops on 23 November 1993. Errors during the closure of each loop were determined and averaged over each of the measurement locations. Measurement uncertainties for any site do not exceed 1.5m. Plotted data yielded a profile similar to that provided by Karrow (1967; **Fig. 1.2**).

1.5.2 LABORATORY METHODS

Sampling of diamict and sand facies for grain-size analysis was completed for sections across the study area. The purpose of diamict sampling was to document regional variability in grain size of massive diamict facies (stratified diamict and deformed laminated facies were not sampled -- see chapter 2). The purpose of the sand sampling was to better understand the relationship of the Sunnybrook to under- and overlying sand formations (the Scarborough and the Lower Thorncliffe Formations). Lenses of sand are contained within the lowest facies of Sunnybrook diamict; models for deformation till suggest that subtill sediments are incorporated into the base of a deforming till. Textural similarity of these lens to the upper Scarborough Formation might indicate rafts of Scarborough within the Sunnybrook, and may support a deformation till origin for the Sunnybrook. Similarly, pillows of sand within the upper Sunnybrook were analyzed for textural similarity to the overlying Lower Thorncliffe Formation.

Sand samples were disaggregated, oven-dried, and sieved to the fine sand-silt threshold (phi size=4) in lab facilities at McMaster University. Sizes measured ranged from -4Φ to +4Φ with a 0.5Φ interval.

Diamict samples (at field moisture conditions) were broken into small pieces and dried in a soil oven. Dried samples were then crushed using a mortar and pestle and placed in a volume of 5% Calgon solution to disaggregate the clay fraction. A "soaking" time of at least two weeks was employed after which the sample could be further processed. Resulting slurries were wet-sieved (using no.200 and no.50 sieves). Particles coarser than silt (retained on the no.200 sieve: >75μm) were oven-dried, weighed, and dry-sieved. The silt/clay slurry was retained for fine-grained sediment analysis. In total, thirty-four diamict samples were processed.

Analysis of the fine-grained fraction was done in Dr.N.Eyles' laboratory (University of Toronto, Scarborough) using a Micrometrics 500 ET Sedigraph. The sedigraph operates on the principles of Stokes' Law for settling velocities of grains in suspension. A continuous stream of the slurry is passed through an enclosed transparent chamber. The pump is turned off and the sample bombarded with X-rays. The intensity of X-rays reaching the opposite site of the chamber is calibrated to settling velocity and grain size curves generated. The sedigraph can record grain sizes as fine as 0.1μm (which requires up to 1 hour for each run). In this study, however, we were interested only in the silt-clay ratio and samples were run to phi size 8 (2μm), the boundary between silt and clay on the Wentworth scale. Run time to reach the 2μm boundary was approximately 15 minutes. Grain size curves for both diamict and sands are included as Appendix B.

1.6 OBJECTIVES OF THIS STUDY

The Quaternary stratigraphy exposed along the Scarborough Bluffs is important to palaeoenvironmental reconstructions along the southern margin of the Laurentide Ice sheet as it contains one of the most complete records of changing environmental conditions during the last interglacial-glacial cycle in eastern North America. There are many unresolved questions concerning the deposits at Scarborough; clearly a reinterpretation of the Scarborough succession affects the interpretation of similar deposits elsewhere (e.g. those at the Lake Erie bluffs described in Dreimanis, 1977).

This study was designed to address the origin of the Sunnybrook diamict, which has received considerable attention in the literature (Eyles and Eyles, 1983, 1984, 1987; Dreimanis, 1984; Gravenor, 1984; Karrow, 1984a, 1984b; Sharpe, 1984; Gravenor and Wong, 1987; Westgate et al., 1987; Hicock and Dreimanis, 1989, 1992a, 1992b; Rutka and Eyles, 1989; Schwartz and Eyles, 1991;). It appears that after nearly twelve years of debate since the introduction of a glaciolacustrine depositional model by Eyles and Eyles (1983), there is little consensus amongst Quaternary scientists in southern Ontario as to the exact depositional origin of the Sunnybrook.

The primary focus of this research was thus to determine the detailed sedimentological characteristics of the Sunnybrook on a regional scale in order to develop a depositional model that accounts for all features of the unit. In doing so, I was also able to test previous hypotheses that the Sunnybrook was either a glaciolacustrine deposit (Eyles and Eyles, 1983) or a subglacial deformation till deposit (Hicock and Dreimanis, 1992a).

CHAPTER 2: FACIES DESCRIPTIONS

2.0 INTRODUCTION

The primary source of data for this study is the field description of sediment facies and the definition of facies associations for the Sunnybrook. A facies is defined as "a body of rock (or sediment) characterized by a particular combination of lithology, physical and biological structures that bestow an aspect ('facies') different from the bodies of rock (sediment) above, below and laterally adjacent" (Walker, 1992a, p.2). Facies analysis should combine observations about any lateral or vertical variation in facies characteristics and the nature of contacts with other sediment types. Interpretation of depositional process can then be made by comparison with similar facies types deposited in modern sedimentary environments (e.g. Collinson and Thompson, 1982). However, more comprehensive interpretation of depositional environments relies on the analysis of 'packages' or associations of facies types which more clearly define the overall environmental setting. Facies associations comprise packages of one or more facies types, often genetically related to one another, and may be used to reconstruct depositional environments through an interpretation of the combined depositional processes for the described sediments. Contacts between facies types and associations are important to define in order to establish the nature of environmental changes that have occurred.

Facies and facies associations described in this study are from the Sunnybrook and portions of the Scarborough, Pottery Road, and Thorncliffe Formations (**Fig. 2.1**). Two dominant facies types are identified in the Sunnybrook, diamict facies (which may be either massive or stratified) and laminated fine-grained facies. Basic descriptions of these facies types and those described from the immediately over- or underlying formations (Thorncliffe, Pottery Road and Scarborough) are given below: a discussion of facies associations will be provided in Chapter 3.

2.1 DIAMICT LITHOFACIES

A diamict is defined as a very poorly sorted sediment consisting of an admixture of a wide range of grain sizes (clay to boulder size; Eyles, N. et al., 1983). All diamicts described in this study area are matrix-supported (i.e. clasts held in suspension in a finer-grained matrix) and may be either massive or stratified (**Fig. 2.1**). Massive diamicts show no textural variability and can be considered as homogenous admixtures of poorly sorted sediment (**Fig. 2.2**); stratified diamicts show some degree of textural sorting and may have variable matrix texture or clast concentrations (**Fig. 2.3**; Eyles, N. et al., 1983). Distinction of massive from stratified diamicts can be difficult; differentiation of the two diamict types has been made in this study on the basis of variability in matrix texture and the abundance of stringers or interbeds of relatively well sorted sediment such as sand or silt. If numerous, closely-spaced, and laterally

Figure 2.1a: Lithofacies logs for sections along the Scarborough Bluffs. Lithofacies code was modified from Eyles et al. (1983, shown in **Fig.1.11**) Grain size is indicated at the top of some logs (e.g. log 9301, reading left to right c-s-sfmc = clay, silt, fine-med-coarse sand) Vertical scale is in metres, horizontal spacing of logs is not to scale on cross-section. Geological unit boundaries are identified and sand units are stippled. The geometry of the Sunnybrook Drift is governed by pre-existing channels cut into the Scarborough Formation.

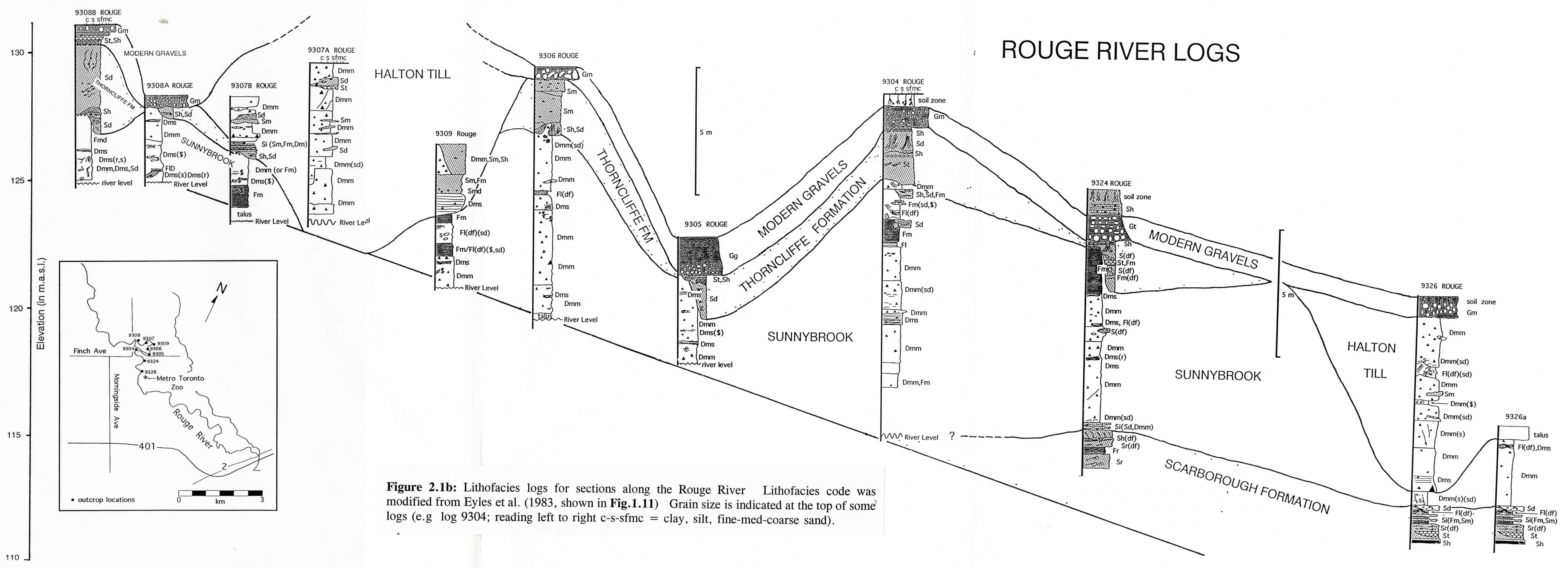
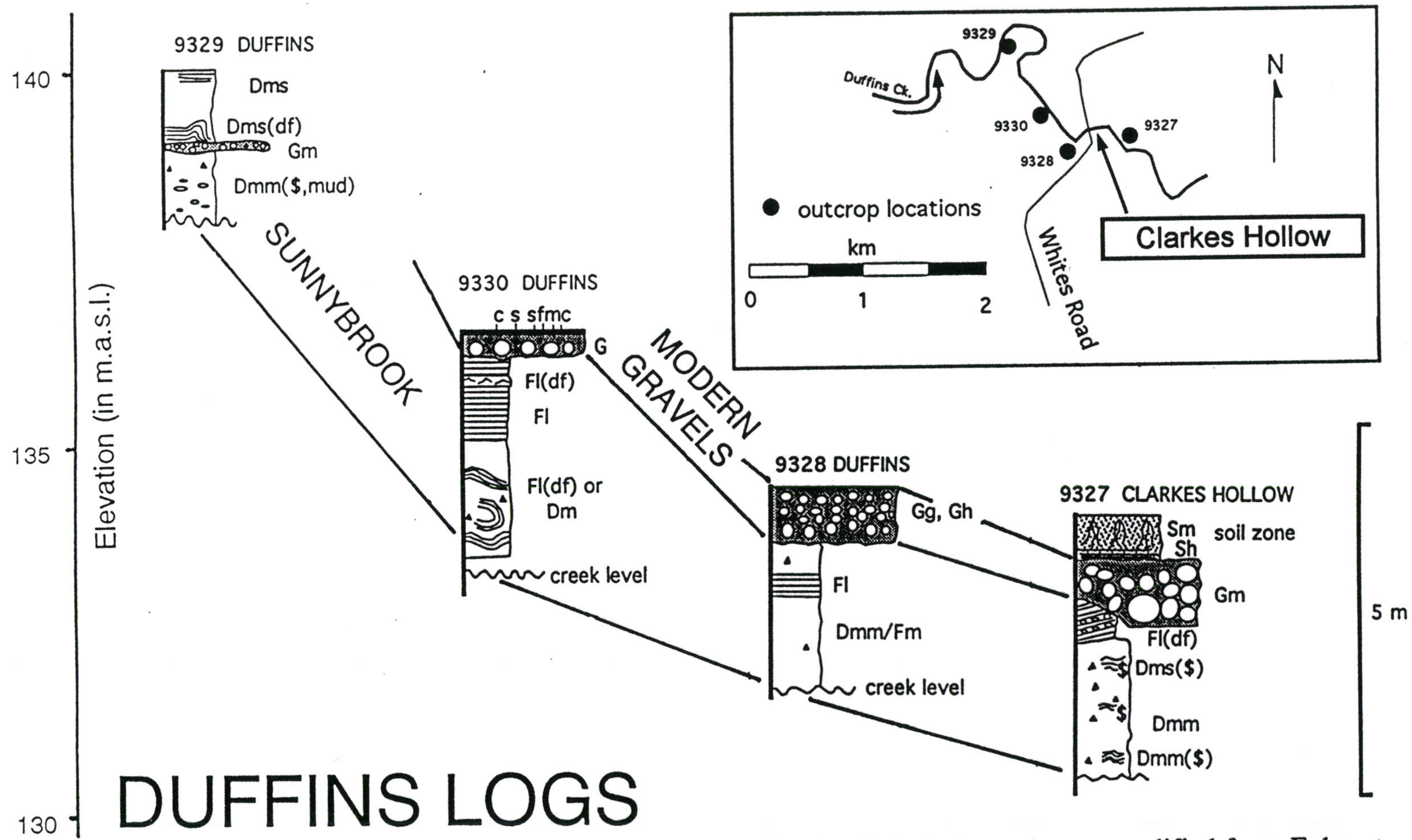


Figure 2.1b: Lithofacies logs for sections along the Rouge River Lithofacies code was modified from Eyles et al. (1983, shown in **Fig.1.11**) Grain size is indicated at the top of some logs (e.g log 9304; reading left to right c-s-sfmc = clay, silt, fine-med-coarse sand).



DUFFINS LOGS

Figure 2.1c: Lithofacies logs for sections along Duffins Creek. Lithofacies code was modified from Eyles et al. (1983; shown in **Fig.1.11**). Grain size is indicated at the top of some logs (e.g. log 9330; reading left to right c-s-sfmc = clay, silt, fine-med-coarse sand).

Figure 2.2: Massive diamict facies. **A)** Blocks of massive, matrix-supported diamict (Dmm) from Rouge River outcrop (section 9306; **Fig. 2.1b**). Massive diamict facies in the Rouge Valley are generally finer-grained and contain fewer and smaller clasts than similar facies exposed along the Scarborough Bluffs. Blocks are $\approx$7.5cm top to bottom. **B)** Massive, matrix-supported diamict (Dmm) from Scarborough Bluffs (section 9311; **Fig. 2.1a**). Knife handle is 9cm long. **C)** Isolated lens of fine sand - light coloured unit above coin - within lower massive diamict facies of the Sunnybrook at Sylvan Park (section 9301; **Fig. 2.1a**). Finer sand stringers are barely visible immediately below the coin (2.6 cm diameter).

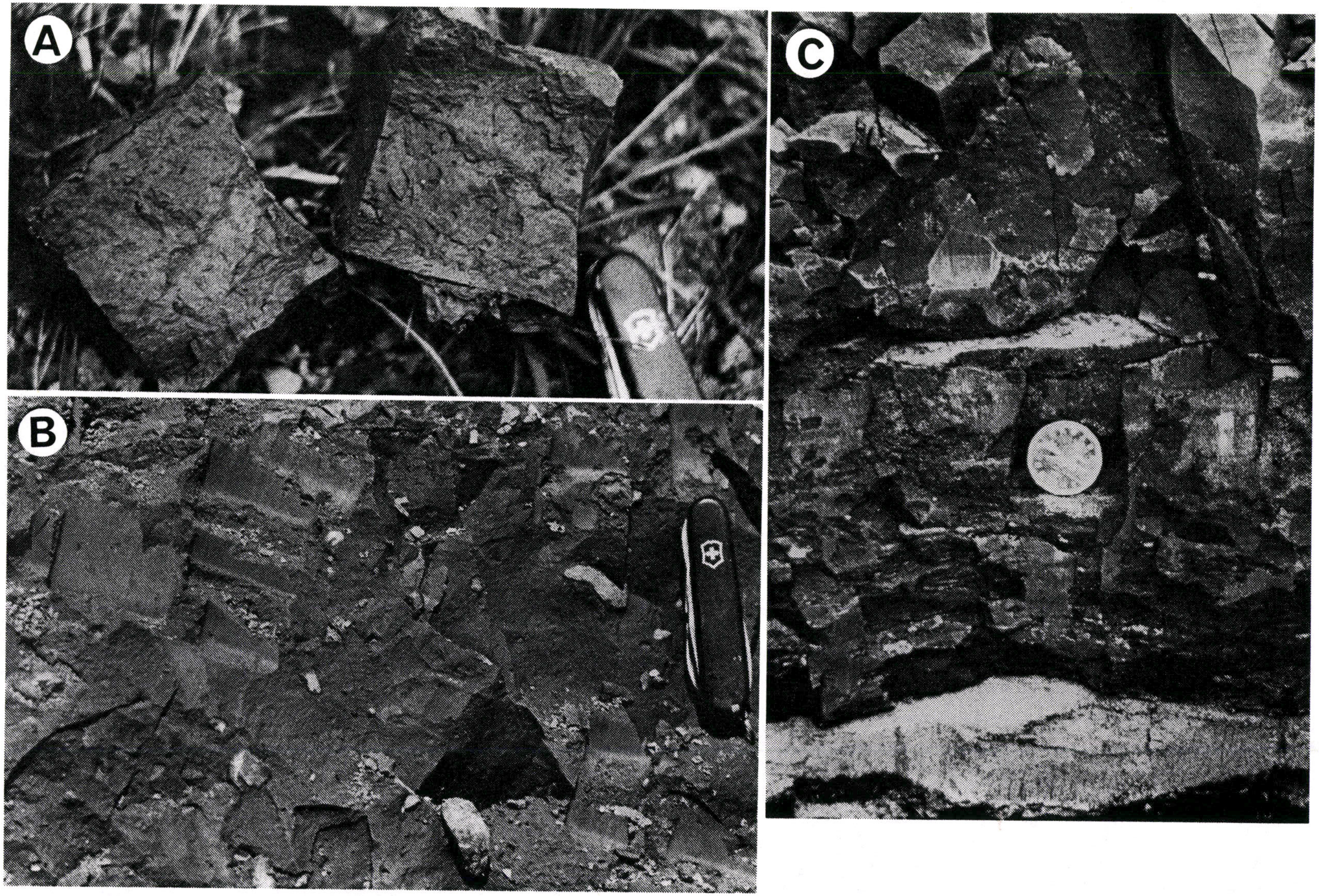
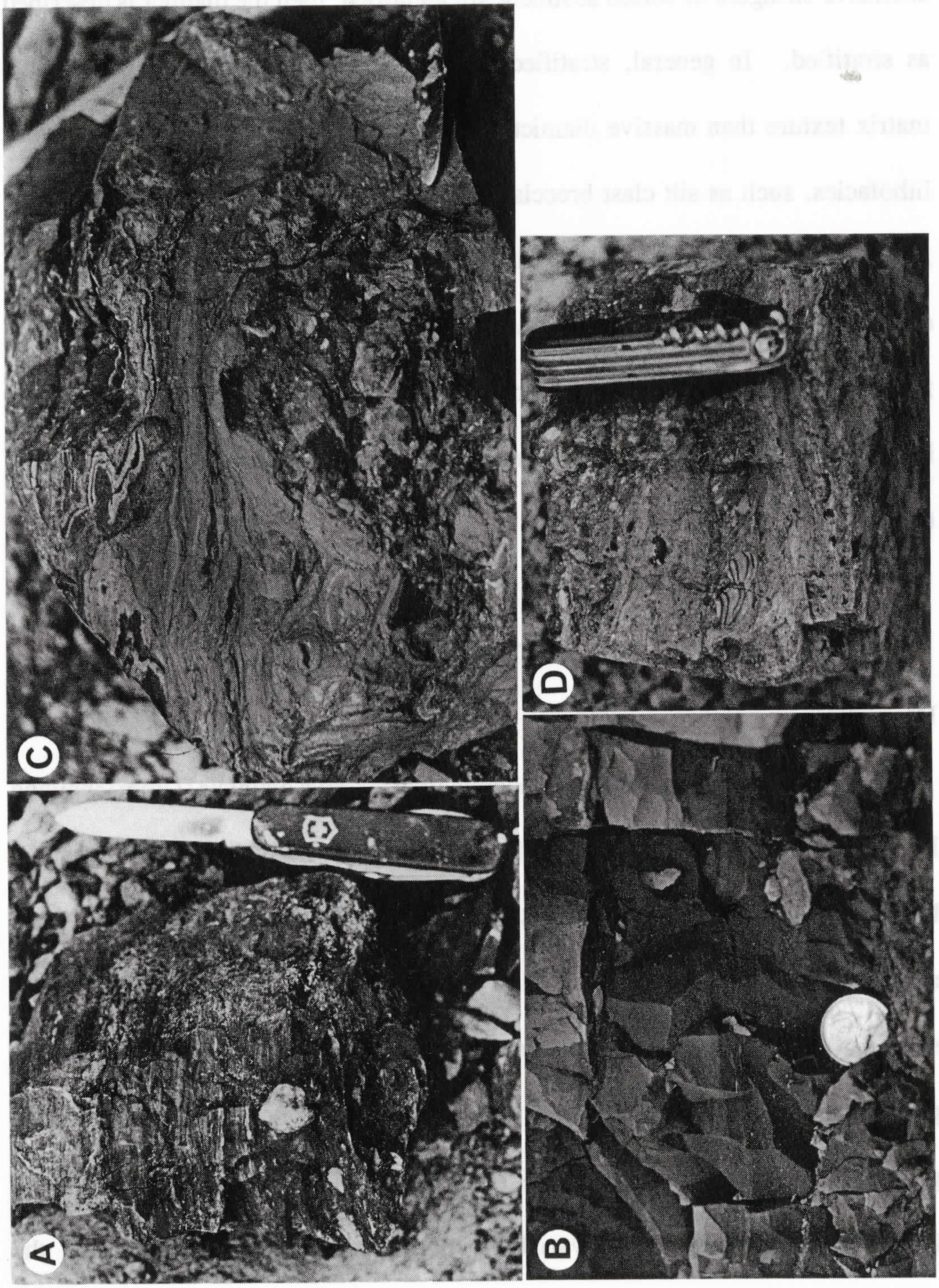

A
B
C

Figure 2.3: Stratified Diamict Facies. **A)** Stratified matrix-supported diamict (Dms) from upper Sunnybrook at Scarborough Bluffs (section 9317; **Fig. 2.1a**). The light coloured banding is formed by silt stringers and a clast is visible in the centre of the photo. Knife blade is 7cm long. **B)** Faint stratification within lower diamict facies at Hi Section (9325; **Fig. 2.1a**). Coin diameter is 2.4 cm. **C)** Dms facies from Rouge River (section 9306; **Fig. 2.1b**). Interbedded clay and silt beds, in the top and left of the block, are contorted. Dark coloured pods in the bottom of the photo are rafts of fine-grained massive diamict. Small stones and silt clasts are present throughout the block. Block is 40cm across. **D)** Chaotic fine-grained facies with rafts of laminated sediments, silt clast breccia and fine-grained diamict within upper Sunnybrook at Rouge section (9304; **Fig. 2.1b**). Knife handle is 9cm long.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extensive stringers of sorted sediment are identified, then the diamict is described as stratified. In general, stratified diamict facies (Dms) have more variable matrix texture than massive diamicts and often include re-worked rafts of other lithofacies, such as silt clast breccia and laminated fine-grained sediments (**Fig. 2.3c**). A fine-grained stratified diamict (Dms) may also have similar characteristics to deformed lacustrine facies (Fl(df)). Differentiation of these two facies is made on the basis of the continuity of laminated beds, which is greater in Fl(df) facies, and on the clast content, which is greater in diamict facies, Dms (**Fig. 2.3**).

2.1.1 MASSIVE DIAMICT (Dmm)

Description

Logged sections comprise predominantly massive diamicts (Dmm) showing limited structure or heterogeneity (**Figs. 2.1 and 2.2**). Individual massive diamict beds range in thickness from 1 to 8 m and some may be traced for up to 9 km along the Bluffs (**Fig. 2.1a**). Massive diamicts consist of poorly-sorted pebble, sand and mud admixtures which lack any distinctive sedimentary structures or pronounced textural differentiation (**Fig. 2.2**). The Sunnybrook diamict in general has a silty-clay matrix (18% sand, 37% silt, 45% clay; Karrow, 1967). However, a relatively high variability of the sand-silt-clay ratio within the Sunnybrook matrix has been documented over the study area (Karrow, 1967; Eyles, 1982; this study; **Table 2.1**). Massive diamict facies sampled at the Bluffs for this study have a relatively coarse-grained matrix (18% sand, 44% silt, 38% clay) and contain scattered clasts up to 15 cm diameter (**Fig. 2.2B**). Many logs at the Bluffs show a weak fining upwards trend in diamict matrix texture defined by an increase in clay content (e.g. sections 9301, 9303 and 9318, **Fig. 2.1**; and several logs of Eyles, 1982). This trend is illustrated by **Figure 2.4** which shows the vertical textural variability of the Sunnybrook diamict at Sylvan Park (section 9301, **Fig. 2.1**). The basal portion of the Sunnybrook diamict often shows a significantly higher sand content (30% sand) than the overlying diamict (≈18%; **Fig. 2.4**).

Massive Sunnybrook diamict exposed along the Rouge River Valley and Highland Creek is finer-grained than that at the Bluffs (matrix texture; 5% sand, 42% silt, 54% clay; **Table 2.1**) and is generally stone-poor with small clasts (a-axes seldom larger than 0.5cm; **Fig. 2.2A**). Preliminary grain size data from Duffins Creek (only 3 samples, **Table 2.1**), however, suggest relatively coarse-grained Sunnybrook matrix (25% sand, 33% silt, 42% clay; **Table 2.1**). A fining-upwards trend, similar to that shown at the Bluffs, was not found in sections in the creeks (**Figs. 2.1b,c**).

Clast content of the Sunnybrook diamict is generally low with clast size ranging from <1 to 15 cm. Clasts as large as 25-30 cm (a-axis) are found in massive diamict facies but are atypical. Clast lithologies within the diamict are mostly limestone and shale (Karrow, 1967).

Although massive diamict facies are generally structureless, some weakly

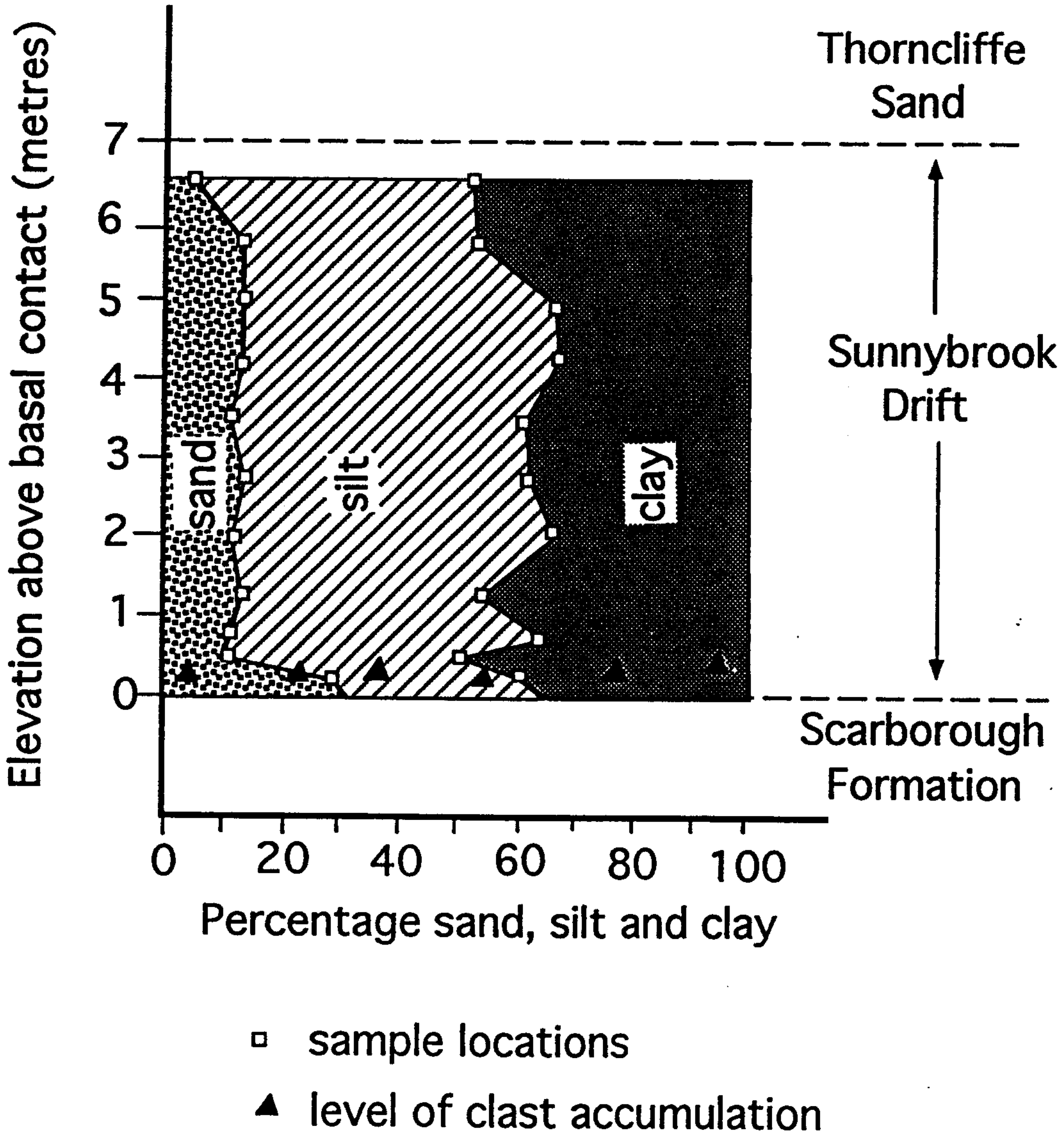


Figure 2.4: Vertical variation in matrix texture for massive diamict facies of the Sunnybrook at Sylvan Park (section 9301). Eleven samples were analyzed with intervals indicated (25cm in lower diamict; 75cm in upper diamict). Filled triangles indicate position of the basal clast horizon. Diamict generally shows uniform texture, except for a sharp increase in sand content at the base, and an increase in clay content towards the top of the Sunnybrook.

Sand/Silt/Clay Percentages for Sunnybrook Diamict

AREA	BLUFFS	BLUFFS	BLUFFS	ROUGE	ROUGE	DUFFINS	DUFFINS	HIGHLAND
unit	Sunnybrook	Sunnybrook	Sunnybrook	Sunnybrook	Sunnybrook	Sunnybrook	Sunnybrook	Sunnybrook
facies	Dmm	n/a	Dms(r),Dm Dmm(c),Dm	Fm,Fmd Dmm,Dmm(s	n/a	Dmm/Fm Dmm	n/a	n/a
study	this study	Karrow '67	Eyles'82	this study	Karrow '67	this study	Karrow '67	Karrow '67
number of measurements	n = 15	n = 15	n = 13	n = 9	n = 3	n = 3	n = 3	n = 5
% sand	18	18	19	5	13	25	30	13
std.dev.	+/- 15	+/- 7	+/- 16	+/- 6	+/- 9	+/- 1	+/- 6	+/- 5
% silt	44	37	39	42	39	33	30	35
std.dev.	+/- 10	+/- 10	+/- 15	+/- 6	+/- 5	+/- 3	+/- 4	+/- 9
% clay	38	46	41	54	48	42	40	52
std.dev.	+/- 8	+/- 16	+/- 21	+/- 8	+/- 5	+/- 3	+/- 10	+/- 14

(not distinguishing "channel" vs "high" sections)

Table 2.1: Sand/silt/clay percentages for the Sunnybrook diamict at the Bluffs and in Highland, Duffins and Rouge Valleys. Facies types sampled are massive diamicts and fine-grained sediments with dropstones (this study), massive and stratified diamicts by Eyles (1982), and unknown facies by Karrow (1967). Both this study and Karrow identify finer grained diamicts in Rouge Valley than diamicts at the Bluffs, and coarser diamicts again in Duffins Creek Valley. Karrow found finer-grained diamicts in the Highland Creek Valley. Boundaries between sediment grain size classes are those of the Wentworth scale (sand/gravel boundary at 2.00mm or -1.0Φ; silt/sand boundary at 63μm or 4.0Φ; clay/silt boundary at 4μm or 8.0Φ). 'Std.dev.' refers to the standard deviation calculated for samples from a particular location.

stratified units are also present. Occasional silt clast breccia horizons occur in massive facies at the Bluffs and isolated sand and silt stringers are common toward the base of massive diamict facies throughout the study area (logged as Dmm(sd) or Dmm($); **Fig. 2.2C**). Discontinuous horizons of cobble-sized clasts are also found at the base of some massive diamict facies exposed along the Bluffs (see section 2.1.3 below).

Massive Sunnybrook diamict facies drape an irregular topography with the thickest diamict units (up to 8 m; **Fig. 2.1a**) preserved in channel forms cut into the underlying Scarborough Formation. Massive diamicts are generally restricted to the lower portion of the Sunnybrook drift in both Bluff and Rouge outcrops where they overlie Scarborough sands with either sharp or interbedded contacts (see section 2.3.3 below). Elsewhere, massive diamicts overlie stratified diamicts with gradational contacts. On the "high" areas between channels massive diamict beds thin to around 1-6m (**Fig. 2.1a**) and have planar upper and lower contacts. The upper contact of massive diamict facies is characterized either by reverse-density loading of the overlying Lower Thorncliffe sand into the massive diamict, or by a gradational contact of massive diamict with overlying stratified diamict (Dms) or deformed laminated sediments (Fl(df); **Fig. 2.1**). In channel sections, massive diamict facies pass upward into stratified diamicts and finally into laminated fine-grained facies (**Figs. 2.1a**).

Massive diamict facies at Bluff and Rouge River sections also contain lacustrine ostracods (see section 1.4.2).

Interpretation

Massive diamict facies are deposited by a variety of processes in a wide range of glacial environments, from subglacial and preglacial to glaciolacustrine and glaciomarine. Texturally homogeneous diamicts form as a result of lodgement (Boulton, 1976; Eyles et al., 1982), or deformation processes (Alley, 1991; Hart and Boulton, 1991; Hicock and Dreimanis, 1992b) in terrestrial subglacial environments; these diamicts are closely associated with other facies (such as fluvial or eolian deposits) indicating terrestrial depositional environments (Eyles and Eyles, 1992). Massive diamicts also originate in subaqueous environments by the processes of 'rain-out' of suspended sediment and ice-rafted debris (Eyles and Eyles 1983; Eyles, C.H. et al., 1985), slumping and resedimentation of poorly sorted sediment (Mills, 1983; Benn, 1989; Eyles, C.H. et al., 1991; Visser, 1991), and iceberg keel turbation and deformation of marine and lacustrine sediments (Thomas and Connell, 1985; Barnes and Lien, 1988; Woodworth-Lynas and Guigné, 1990; Dowdeswell et al., 1994). Massive diamicts formed subaqueously are closely associated with other sediments and features (such as fossils or ichnofacies) indicating marine or lacustrine conditions. Successful environmental interpretations of massive diamict facies must therefore be based on a comprehensive analysis of **all** aspects of the diamict facies, their associated sediments and the nature of contacts between them, and the spatial distribution of the entire depositional succession (Eyles, N. et al., 1983).

The massive diamicts of the Sunnybrook form part of a thick succession of predominantly lacustrine deposits preserved on the margins of the Lake Ontario Basin. Thus, a lacustrine depositional setting for the Sunnybrook must be seriously considered. Massive diamict facies of the Sunnybrook closely resemble "rain-out" diamicts formed by the settling of suspended fines and release of coarser debris from icebergs in a subaqueous environment (Eyles and Eyles, 1992). Suspended fines entering the lake in meltwater plumes, either directly from the ice sheet (i.e. via sub- or englacial streams or rain-out from icebergs) or from glaciofluvial outwash streams would settle to the lake floor as a blanket of fine-grained mud. Relatively rapid sedimentation rates and a constant and abundant supply of fines would produce an unstratified deposit (Kranck, 1986). Coarser debris supplied by ablating icebergs floating in the lake would add the clast component to form a massive diamict.

The drape-like geometry of the Sunnybrook on the underlying topography supports this interpretation of the diamict as a subaqueous 'rain-out' deposit. However, thicker units of massive diamict preserved in topographic lows on the surface of the underlying Scarborough delta suggest that some redistribution of the sediment has occurred. It is probable that slumping of unstable fine-grained diamicts into lows was synchronous with 'rain-out' processes and resulted in the intimate association of massive 'rain-out' and resedimented diamict facies. The presence of common sand lenses or stringers and occasional thin silt clast breccias within massive diamict facies supports the interpretation of limited resedimentation processes. Sand lenses and stringers are associated with slumps directed into the channel areas during deposition of the Sunnybrook diamict, and the breccias result from the downslope resedimentation and disaggregation of pre-existing silt beds (Eyles, N. et al., 1983).

The presence of common unbroken ostracods (3 species) in massive Sunnybrook diamict facies (Westgate et al., 1987; Rutka and Eyles, 1989) is also supportive of an origin by passive 'rain-out' processes in a lacustrine setting. Mean temperature, depth, and distance-from-shore preferences for the two ostracod Candona species, present in lower massive diamicts are 5.4°C-12°C, 32-140m, and 3-20km; mean preferences for Darwinula stevensoni, found only in the upper Sunnybrook massive diamict, are 21.4°C, 2.3m, and 0.3km (Westgate et al., 1987; **Table 1.4**). These data suggest that the lake into which most of the Sunnybrook was deposited was likely large, deep and cold; towards the end of the interval of diamict deposition, warmer and shallower lacustrine conditions prevailed. The weak fining upwards trend identified within massive diamicts at the Bluffs also suggests a changing sediment supply which may relate either to changing water depths or ice proximity.

An alternate process that may have been responsible for the formation of massive diamicts of the Sunnybrook in a lacustrine setting is sediment mixing and homogenisation caused by iceberg scour processes. Studies on modern (Barnes and Lien, 1988; Dowdeswell et al., 1994) and on ancient (Woodworth-Lynas and Guigné, 1990) ice proximal glaciomarine and glaciolacustrine environments find iceberg scour to be a dominant process in the creation of structureless, poorly sorted sediment. Fine-grained subaqueous sediments are extensively turbated and mixed by the grounding keels of large bergs, to such a degree that primary sedimentary structures are destroyed. Dowdeswell et al. (1994) describe nearly 90% of sediment within recovered cores from glaciomarine environments off the east coast of Greenland as massive diamicton, resulting from iceberg keel turbation. This process may have been significant during accumulation of the Sunnybrook diamict. However, in the absence of any identifiable iceberg keel scours or preserved remnants of undisturbed sediment it is impossible to confidently interpret this process for the Sunnybrook. It has also been noted that free-falling particles from ablating icebergs may also significantly turbate soft sediments into which they fall (Thomas and Connell, 1985; Gilbert, 1990). This process may also have contributed to the mixing and homogenisation of Sunnybrook diamict.

2.1.2 STRATIFIED DIAMICT (Dms)

Description

Stratified diamict facies are differentiated from massive diamict facies on the basis of variability in matrix texture, and/or the presence of 'abundant' silt or fine sand stringers, or common horizons of clasts, diamict clots and silt clast breccia within the matrix (**Fig. 2.3**). Variations in matrix texture are shown by colour changes or differential weathering patterns on the diamict surface, and identify predominantly horizontal stratification patterns (**Fig. 2.3B**). Textural variability is generally slight, ranging from silty clay to clayey silt (**Fig. 2.1**). Subtle stratification in Sunnybrook diamict facies has been noted in X-ray images of diamict blocks by Eyles et al. (1987). Some stratified diamicts contain common, thin (less than 0.5cm thick; **Fig. 2.3A**) stringers of silt and fine sand (this study; Gravenor and Wong, 1987).

Stratified diamicts often contain fine-grained lacustrine materials that have been reworked, such as deformed units of laminated silt and clay (**Fig. 2.3C**) or small rafts of intact laminated sediments (**Fig. 2.3D**). Deformed laminated facies may be brecciated or may show features indicative of deformation by downslope flow such as flow noses or overturned folds (**Fig. 2.3C**).

Individual beds of stratified diamict are relatively thin, generally less than 0.5m thick (**Figs. 2.1** and **2.5**); stratified facies are found predominantly as interbeds within thicker units of massive diamict (**Fig. 2.5**), or in association with finer-grained facies in the uppermost Sunnybrook (**Figs. 2.5** and **2.6**). Stratified diamicts are particularly common in Sunnybrook outcrops in the creeks (**Figs. 2.1b,c**).

Interpretation

Stratified diamicts are not usually reported from terrestrial glacial environments but are a common component of many subaqueous glacial depositional systems (Eyles, C.H. et al., 1985). In subaqueous settings matrix stratification may result from changing suspended sediment input and/or changing current velocities (Orheim and Elverhoi, 1981; Anderson et al., 1984; Eyles,

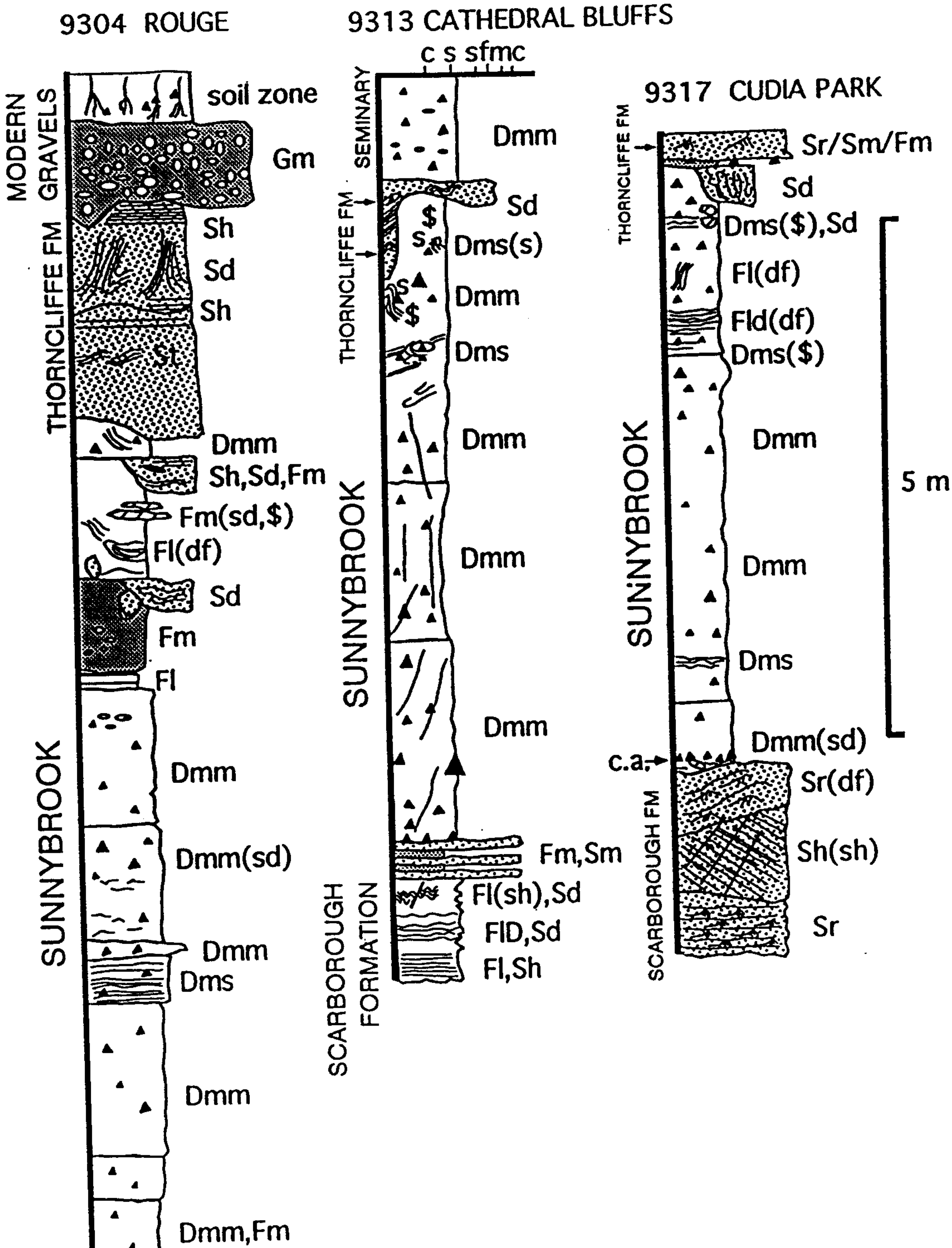


Figure 2.5: Sediment characteristics of Dms/Fl(df) facies in the upper Sunnybrook diamict along the Bluffs (sections 9313 and 9317; **Fig. 2.1a**) and in the Rouge Valley (section 9304; **Fig. 2.1b**). Units of Dms facies do not exceed 0.5m in thickness. These logs also illustrate the commonly loaded upper contact between the Lower Thorncliffe Formation and the Sunnybrook diamict. The relief of the contact is commonly 1m, although pillows with up to 2m of relief exist.

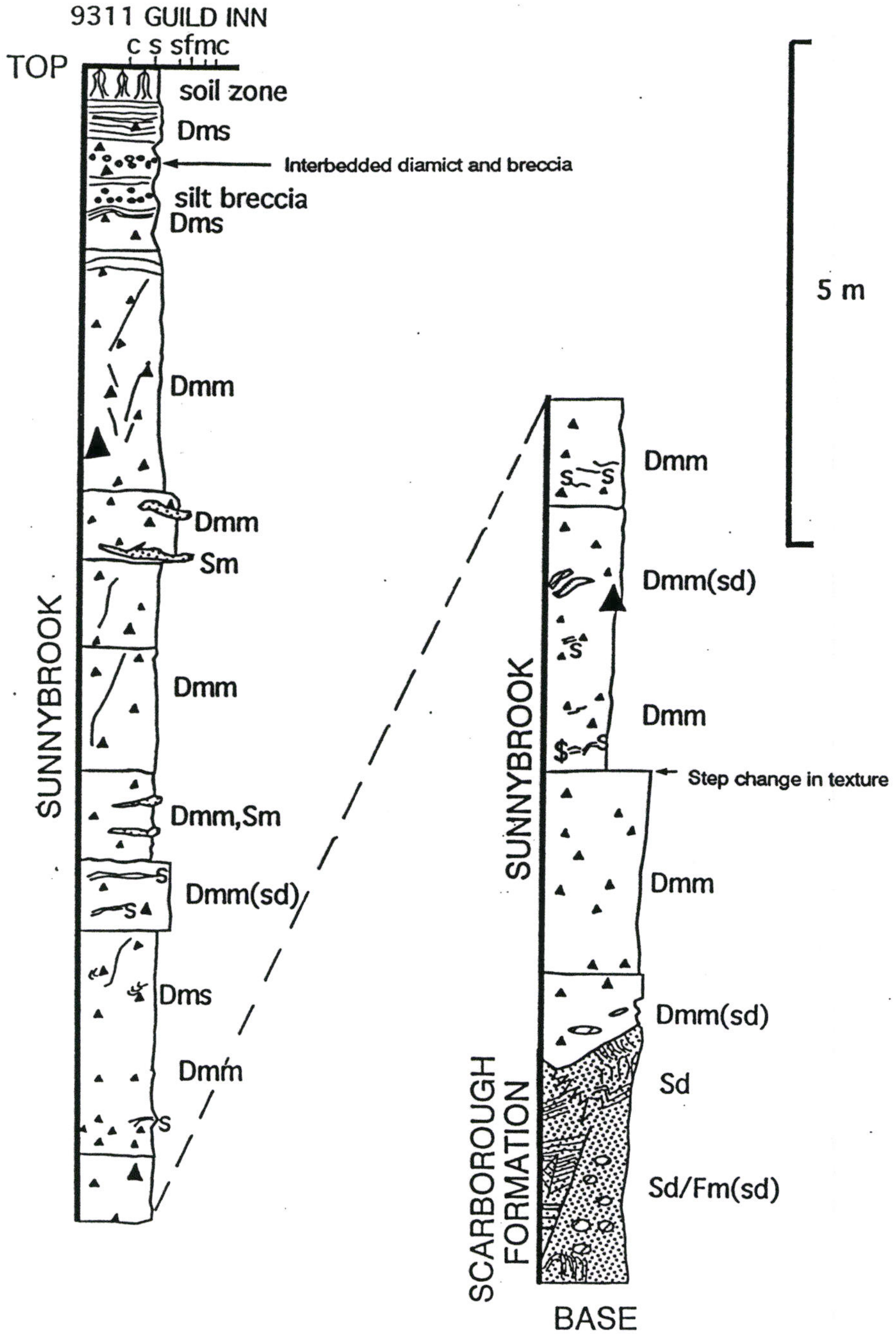


Figure 2.6: Guild Inn log (9311; **Fig. 2.1a**) located in a "channel" topographic setting in the eastern Bluffs. Interbedded stratified diamict and silt clast breccia horizons can be seen at the top of the log. Diamict is finer-grained in the upper part of the section -- a step change in texture is indicated in the right hand column. Common sand lenses and stringers within the diamict are associated with slumps directed into the channel during deposition of the Sunnybrook's massive and stratified diamict facies.

Figure 2.7: Fold and flow structures within diamict facies; these structures probably formed as a result of downslope slumping of beds. **A)** Small scale folds in silt and clay laminations within diamict (logged as stratified diamict, Dms, section 9313; **Fig. 2.1a**). These probably result from limited downslope slumping of the beds. Silt and clay laminae are disturbed by the clast (just to the left of the knife) which may be interpreted as a dropstone. Knife handle is 9 cm long. **B)** Plan view of folded and contorted Sunnybrook facies containing disturbed laminated silt (represented by voids in photo as silt is preferentially removed by stream erosion) and clay beds at Rouge section 9308. Clasts on the surface have been deposited by the modern stream. Ice axe handle is 80cm long.


A
B

C.H. and Lagoe, 1990). Even slow moving currents (less than 1cms^{-1}) can cause the separation of coarser and finer size grades during settling of suspended sediment and produce textural banding in the diamict matrix (Eyles, C.H. and Lagoe, 1990). Stringers and lenses of sand and silt identified within the lowermost diamict facies of the Sunnybrook probably result from intermittent traction current activity on the basin floor. Such currents may have been generated by underflows entering the basin probably as a result of storm activity.

Many of the features shown by the stratified diamicts of the Sunnybrook may be attributed to the deformation and resedimentation of pre-existing sediments. Flow noses (described by Eyles and Eyles, 1983), rafts of laminated silts and clays, and silt clast breccias found within stratified Sunnybrook facies indicate resedimentation of diamict together with laminated deposits. Resedimentation was probably caused by the failure and slumping of fine-grained, unstable sediments on relatively low angle slopes. Incomplete mixing of sediments and simple folding of sediment rafts in the upper Sunnybrook (**Figs. 2.5, 2.6** and **2.7**) suggests short-travelled slumps. Slumping and resedimentation of fine-grained sediments is commonly reported from glaciolacustrine environments (Mathews, 1956; Harrison, 1975; Eyles and Eyles, 1992;) and may be triggered by a number of factors including over-steepening of depositional slopes, seismic shock, isostatic readjustments or storm wave activity (Ness and Kulm, 1973; Kostachuk and McCann, 1987; Walker, 1992b).

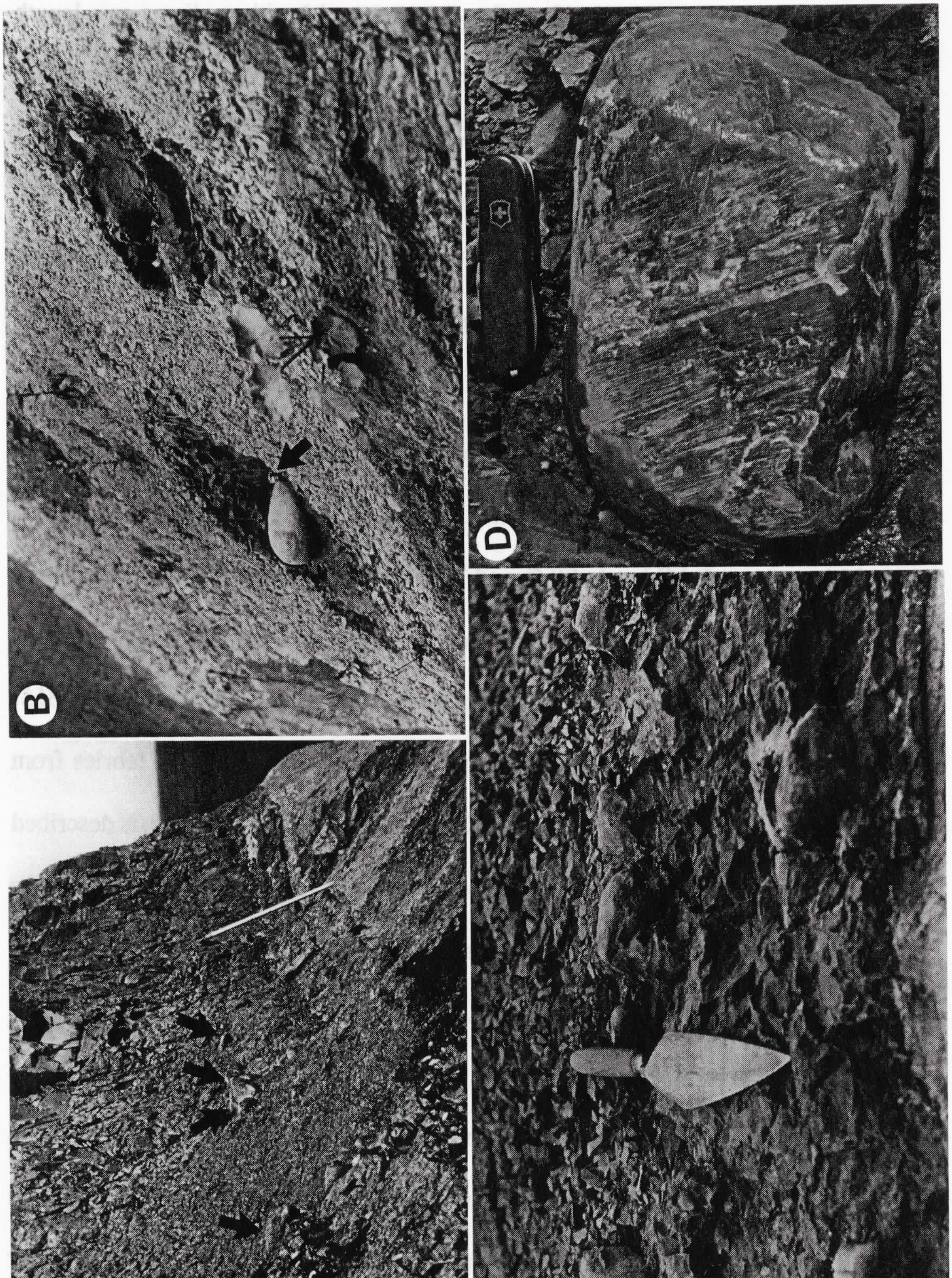
An additional factor that should be considered when discussing the origin of stratified and resedimented diamicts of the Sunnybrook is the effect of iceberg grounding. The process of iceberg keel turbation of lake bottom sediment was discussed with reference to the formation of massive facies of the Sunnybrook through complete mixing and homogenisation of pre-existing sediments (section 2.1.1). **Incomplete** mixing and disturbance of pre-existing stratified sediments by grounding iceberg keels could result in the formation of stratified diamicts similar to those described here.

2.1.3 CLAST HORIZONS WITHIN DIAMICT FACIES

Description

Clast horizons, consisting of planar concentrations of clasts within the diamict, were found in the lowermost portion of the Sunnybrook diamict at several sections along the Bluffs (sections 9301, 9313, 9314, 9314A, 9317, 9323, and 9325: **Fig. 2.1a**), typically less than 0.5 metre above the Sunnybrook's contact with the underlying Scarborough Formation (**Fig. 2.8A**). Clast horizons are associated with a sharp break from coarser to finer diamict matrix texture in the lowermost Sunnybrook (**Fig. 2.4**) and are discontinuous over several metres of section; clasts within these horizons may either be in contact with one another (**Fig. 2.8C**) or unevenly-spaced (**Fig. 2.8B**)). Most commonly, clasts form layers one-clast thick; however in one instance, two clast horizons are stacked one on top of the other, separated by 0.2m of diamict (**Fig. 2.8C**). Clast lithologies are predominantly carbonates and shales and clast shapes are sub-rounded to sub

Figure 2.8: Basal clast horizons at the Bluffs. Scarborough formation underlies the Sunnybrook in each photo. **A)** Clast horizon within the Sunnybrook (several clasts are arrowed) resting 0.2m above the contact with Scarborough Fm. at Sylvan Park (section 9301; **Fig. 2.1a**). Clast horizons are discontinuous and individual clasts show a variety of size, shape and a-axis orientation. Ice axe handle is 80cm long. **B)** Boulder excavated from clast horizon at Springbank Ave. (section 9314; **Fig. 2.1a**). Knife (arrowed - pointing out of the photo) lies parallel to a-axis at 110° (down dip direction). The top of the clast pictured is striated parallel to a-axis, with other scratches subparallel to main striae. **C)** Clast horizons at Cudia Park (section 9317; **Fig. 2.1a**). Clasts are organized into two stacked horizons; some clasts are in contact with one another. Trowel is 25 cm long. **D)** Plan view of boulder excavated from clast horizon at Sylvan Park (section 9301; **Fig. 2.1a**). Clast a-axis is oriented at 190° (southward dip 5°). Striae are oriented at 255° on the flat-topped stone. This clast is one of few examples with such prominent striations. Note several sets of criss-crossing striae (scratches) on the right hand side of the stone more parallel to a-axis. Knife handle is 9cm long.


A
B
C
D

-angular. Clasts range in size from 2 to 36 cm (a-axis) with median a-axis length of 8 cm. Sixty-five percent of the clasts are prolate (**Table 2.2**; axial ratio a/b greater than 1.4; Rappol, 1985) and hence are suitable for fabric analysis.

Clast fabrics measured from three separate clast horizons at sites along the Bluffs (9301, 9317, and 9325) show a variety of a-axis orientations (**Fig. 2.9**). Only the clast horizon at Sylvan Park (9301) has a weak preferred NE-SW orientation of clast a-axes (**Fig. 2.9**). Clast orientation data at section 9301 is statistically significant (n=41), with mean orientation of 244° and radius of confidence (RAC at 95% Confidence Level) of 17° (**Table 2.2**). Sites 9317 and 9325 have large RAC levels (85% and 73% respectively), and hence the inferred fabric orientation is random. Three other sites along the Bluffs had clast horizons present, but lacked sufficient clasts to produce statistically reliable results (9313, 9314, 9323; **Table 2.2**). Fabric strengths were calculated for clast fabrics from horizons at sections 9301, 9317 and 9325 using the eigenvector analysis described by Mark (1973). S_1 eigenvalues, representing the strength of clustering about the eigenvector V_1 (the direction of maximum clustering), for the sites are 0.664, 0.541 and 0.694 respectively (**Table 2.3**). The S_3 eigenvalue represents strength about the axis of minimum clustering (V_3).

Clasts measured in basal clast horizons of the Sunnybrook also show both single and multiple sets of striae. Fourteen of 77 clasts (18%) in these horizons are striated with all striations found on the tops of clasts. Only a small number

Site no.	total n	n-crit	n-str(1)	% str(1)	n-str(x)	% str(x)	n-str(ob)	% (ob)	n-no dip	% no-dip
9301	**55**	**40**	**4**	**10**	**2**	**5**	**2**	**5**	**21**	**53**
9313	3	1	0	0	0	0	0	0	1	100
9314	8	5	0	0	0	0	1	20	0	0
9317	**34**	**23**	**3**	**13**	**0**	**0**	**1**	**4**	**13**	**57**
9323	9	5	1	20	0	0	0	0	3	60
9325	**25**	**14**	**1**	**7**	**0**	**0**	**1**	**7**	**4**	**29**
total	**114**	**77**	**8**		**2**		**4**		**38**	

total n: total number of clasts measured in horizon
n-crit: total number of clasts with a/b ratio >1.4
n-str(1): total number of clasts with one set of striae
n-str(x): total number of clasts with criss-crossing striae
n-str(ob): number of clasts with one set of striae striking oblique to a-axis
n-no dip: total number of clasts with "zero-dip"
total (bolded): sum of each column for sites 9301, 9317 and 9325

Table 2.2: Clast fabric data for basal clast horizons identified within the lower Sunnybrook diamict facies at 6 sections along the Bluffs, expressed in absolute numbers and in percentages. Only prolate stones are used in the analysis. Few clasts are striated parallel to the clast's a-axes; some striated stones show criss-crossing striation patterns. Many clasts show low angle (<6°) or zero dips.

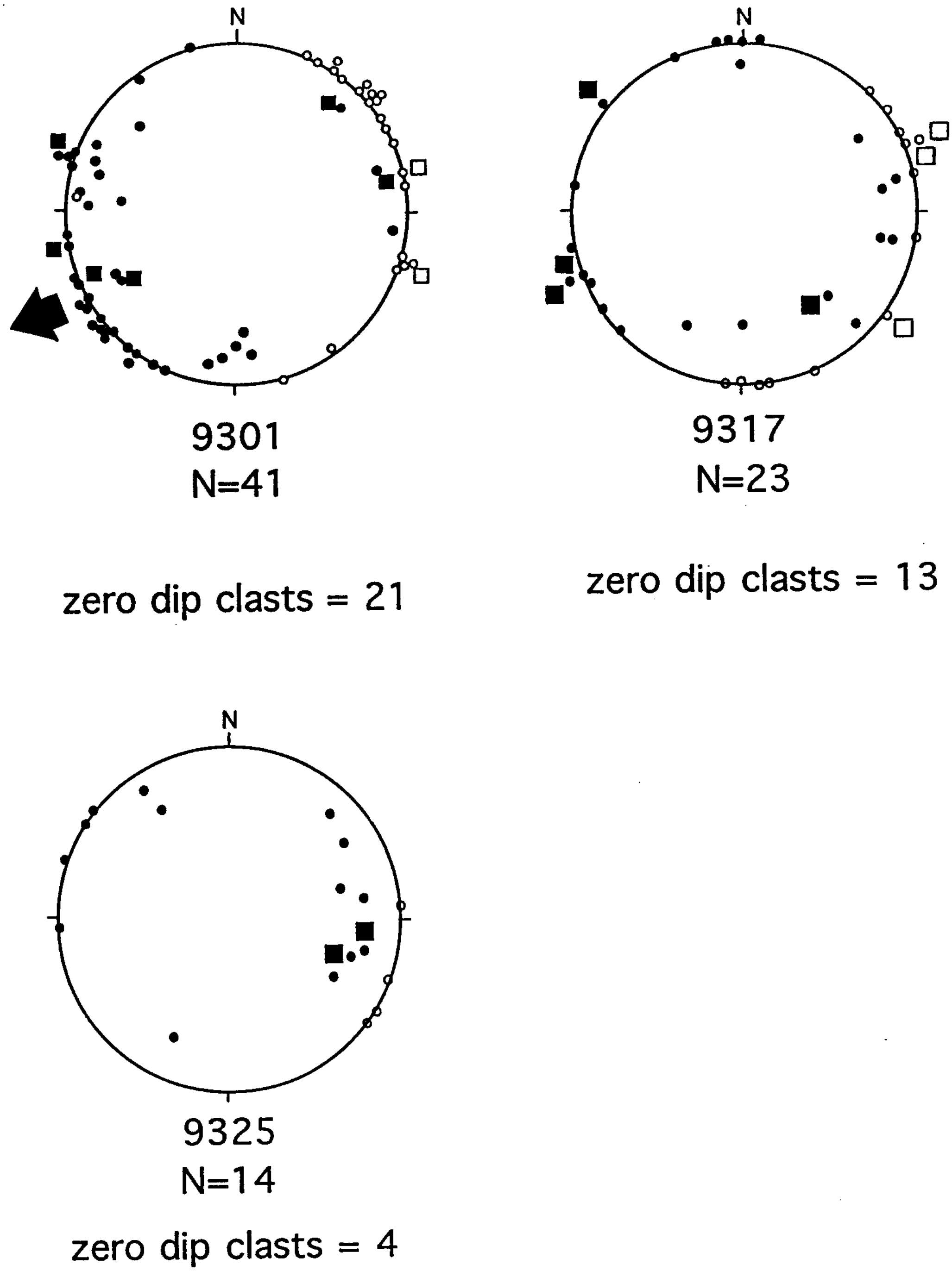


Figure 2.9: Clast orientation and dip data for clast horizons in lowermost Sunnybrook diamict exposed at sections 9301, 9317 and 9325. "Zero-dip" clasts are plotted twice (black and open circles) to represent the two possible orientations they may have. Black and open squares refer to the orientation of striae on striated clasts; open squares are plotted for striae orientations on zero-dip clasts; only clasts having one set of striae are shown here. Clast a-axis fabrics measured in this study suggest considerable variability in orientation, but show a moderate preferred NE-SW alignment for section 9301 (arrowed).

site	n =	S_1	S_2	S_3	dip dir	dip	RAC
9301	41	0.664	0.317	0.019	244°	4°	17°
9317	23	0.541	0.437	0.022	70°	3°	85°
9325	14	0.694	0.279	0.027	103°	7°	73°

Table 2.3: Eigenvalue and eigenvector statistics (eigenvector analysis of Mark, 1973) for clast fabric from basal clast horizons. Calculations were compiled using QUIKPLOT (a plotting program for orientation data, written by D. van Everdingen and J. van Gool, 1990: Department of Earth Sciences, Memorial University). "Dip dir" refers to the down-dip direction of the primary eigenvector (V_1), which represents the predominant orientation of the a-axis. S_1, S_2, and S_3 eigenvalues are measures of fabric strength, and are plotted on **Figure 2.10**. RAC refers to the Radius of Confidence for the Fisher 95% Confidence circle diameter - a large RAC is associated with significant uncertainty in the measurements.

of clasts have a single set of striae parallel to a clast's a-axis (8 of 77 clasts; **Table 2.2**), suggesting a weak preferential NE-SW orientation (**Fig. 2.9**). Others have a single set of striae striking at oblique angles to the clast a-axis (4 of 77 clasts), and show the same NE-SW orientation (**Fig. 2.9**). Few clasts (2 of 77) have multiple sets of striae (**Fig. 2.8D**), with striae striking obliquely to the a-axis. These were not plotted on **figure 2.9**. As well, all clast fabric and associated striae data are provided in Appendix D.

Interpretation

Clast horizons are reported in several types of glacigenic sediments, including those formed in subglacial environments (Dreimanis, 1976; Boulton, 1978; Kruger, 1979; Clark, 1991) and subaqueous environments (Hansom, 1983; Eyles, C.H., 1988, 1994). Horizons can develop as clasts are selectively deposited (by water or by ice) or when finer grained sediments are winnowed away leaving a clast lag (Eyles, C.H., 1994). Once clasts are fixed in the substrate, their exposed surfaces may be subjected to abrasion and striation by overriding ice, icebergs, or seasonal lake ice (Eyles, C.H., 1994).

The characteristics of the Sunnybrook's clast horizons are summarized in the following table.

(1) clast fabrics measured at three sites show weak preferred (NE-SW) orientation of a-axes for only <u>one site</u> (Sylvan Park; section 9301); the other two sites show random orientations (**Fig. 2.9**);
(2) clasts in horizons are <u>poorly striated</u>; several clasts have multiple sets of striae (**Table 2.2**);
(3) clast horizons are found only in the <u>base</u> of the Sunnybrook, and correspond to a sharp break from coarser to finer diamict matrix texture (see **Fig. 2.4**);
(4) clast horizons are found only at sites on the <u>relative highs</u>, and not at sites in channels;
(5) clast horizons are found within diamicts which are interpreted as glaciolacustrine.

From these characteristics, the nature of the depositional setting can be inferred.

The random and weak-to-moderate fabric strengths (S_1 eigenvalues = 0.661, 0.541, 0.694; **Table 2.3**) measured from the Sunnybrook clast horizons are compared to strengths from glacigenic diamicts of a variety of origins (Dowdeswell and Sharp, 1986). The strongest measured fabrics are those from melt-out tills and undeformed lodgment tills having S_1 eigenvalues greater than 0.62 and S_3 eigenvalues of approximately 0.05 (**Fig. 2.10**). Fossiliferous diamictons (Domack and Lawson, 1985 fide Dowdeswell and Sharp, 1986),

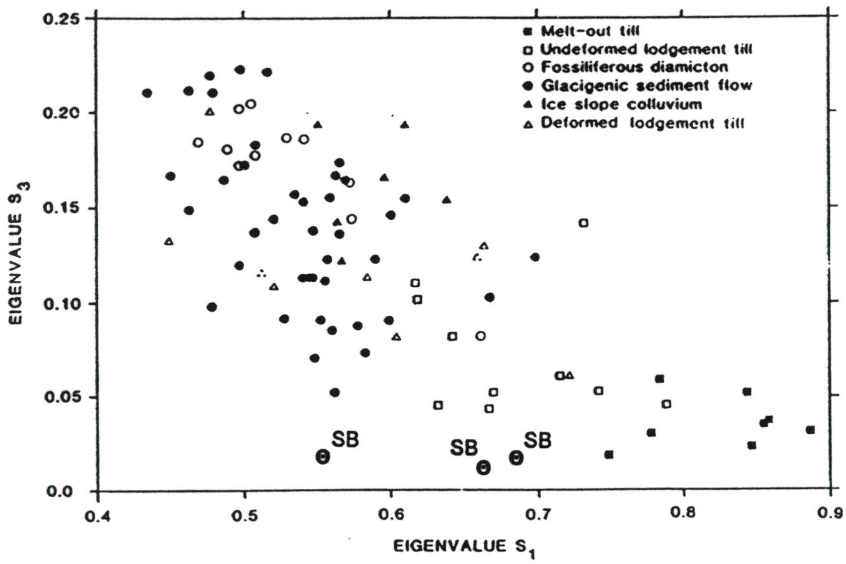


Figure 2.10: The pattern of S_1 and S_3 eigenvalues representing fabric strength in several facies of glacial sedimentation (from Dowdeswell and Sharp, 1986). The three 'dotted circles' (superscript 'SB') are data from this study from sites 9301, 9317, and 9325 (see Table 2.3).

interpreted as ice-rafted sediment, show weaker fabric strength (S_1 = 0.45-0.65). Eigenvalues calculated for clast fabric data from clast horizons of the Sunnybrook at three sites along the Bluffs (**Table 2.3** plotted on **Fig. 2.10**) fall close to those representing "**undeformed lodgement till**". However, interpretation of these data is cautioned as the uncertainty in the measurements (represented by the 95% confidence levels; **Table 2.3**) is high (RAC's range from 17 to 85° for the three sites). In addition, the low angle or zero dips for clasts measured in the Sunnybrook clast horizons (**Fig. 2.9**; **Table 2.2**) are atypical of lodgement till facies (Gravenor and Wong, 1987). Based on measured fabric data of the present study and on the results of Dowdeswell and Sharp (1986), the environment in which horizons formed cannot be uniquely determined. Clast fabric data from the present study shows that clast a-axes have a preferential orientation at only one of three measurement sites. This suggests that the process which caused the preferential clast alignment was not critical to the **emplacement** of the clast horizons, and hence, that a model for the formation of horizons may comprise two or more distinct processes: one process to emplace clasts in the substrate, and a second process to preferentially align clasts in select horizons. In the glaciolacustrine environment proposed for deposition of the Sunnybrook, clasts can either be emplaced by rain-out from ablating icebergs or winnowed from the accumulating diamict sediments; the preferred orientations at select sites developed in response to lake floor scour by seasonal lake ice and/or iceberg keels (see discussion below).

The second characteristic of the clast horizons examined was the nature of striations on the clasts. Because some of the clasts within the clast horizons are striated, it was inferred that the clasts were once influenced by subglacial processes, presumably as part of a lodgement till, in which clasts horizons and pavements are commonly documented (Kruger, 1979; Sharp, 1982). However, the small percentage of striated clasts within the Sunnybrook's clast horizons (14 of 77 clasts [18%] **Table 2.2**) is atypical of lodgement till; Sharp (1982) found that 65 percent of 100 boulder-sized clasts in lodgement till were striated. The lack of striated clasts in the Sunnybrook's basal clast horizons may therefore preclude a subglacial model for formation of the horizons. The preferred orientation of striae on clasts (for clasts with only one set of striae) within the Sunnybrook's clast horizons is NE-SW at only one section (9301), but is random at two other sections (9317 and 9325; **Fig. 2.9**). Consistent orientations of striations and clast a-axis are utilized as a diagnostic criteria of lodgment tills by Kruger (1979).

The nature of the striations on clasts in the Sunnybrook's clast horizons do not suggest that horizons developed in a subglacial position. The low percentage of striated clasts and predominantly random orientations of striae, inconsistent with clast a-axes orientations at section 9301, contrast to known fabrics of lodgement tills (Kruger, 1979; Sharp, 1982). It is not known, however, whether striations on clasts developed in deposits which pre-existed the Sunnybrook and were later re-worked, or whether striations were added once the clasts were deposited in the Sunnybrook's depositional environment. The development of striations on clasts may have acted concurrent to the process which oriented clast a-axes.

The occurrence of clast horizons on the relative highs and in the base of the Sunnybrook suggests that environmental conditions, responsible for formation of clast horizons, existed only on highs in the substrate and only during initial stages of Sunnybrook deposition. This suggests that basal clast horizons formed in shallow water conditions, which were present during deposition of the lowermost Sunnybrook diamict. It also suggests that the formation of clast horizons in channel areas (e.g. topographic lows in the substrate) was precluded by the increased lake depth. Thus, the environment in which horizons were deposited is characterized by shallow glaciolacustrine conditions.

Shallow, density driven currents are common in glaciolacustrine and glaciomarine environments which can winnow bottom sediments to expose the surface of clasts (Eyles, C.H., 1994). As discussed in section 2.1.1, icebergs and seasonal ice would have been present in the Lake Ontario basin during deposition of the lowermost Sunnybrook. Depending upon the depth of the lake at this time, seasonal lake ice may have had some effects on the lake bottom sediments (Grass, 1983) and on accumulated clast horizons. The erosive and striating capabilities of seasonal ice have been demonstrated by Dionne (1979), in which he reviewed the geomorphological features associated with seasonal lake ice in subarctic Quebec. Ice push ridges and grooving features, as well as abrasion by ice (e.g.

lake ice striations) were noted in several localities. Several of Dionne's (1979) figures (especially figure 11) illustrate the parallel grooving in bottom sediments in shallow embayments which developed as seasonal ice pushed boulders landward. This parallel grooving by seasonal ice could probably produce a preferred orientation for clast major axes for clasts in a single embayment and may have left bottom sediments in other embayments unaffected. Such a process may have occurred in the shallow lacustrine conditions which persisted in the beginning of the Sunnybrook interval on the topographic highs in the substrate along the Bluffs. Slight changes in depth may preclude the formation of clast horizons in certain locations, and are likely responsible for the spatial variation in the preferred orientation of clast axes observed within the Sunnybrook's clast horizons in the present study. Striations on a **limited** number of the clasts in the Sunnybrook horizons may be due to inconsistent abrasion by seasonal lake ice.

In previous sections (1.4.2, 2.1.1 and 2.1.2), a subaqueous model for the deposition of the Sunnybrook diamict was established, based on lithofacies and ostracod evidence, which supports previous interpretations of predominantly lacustrine conditions existing in the Toronto region for much of the Wisconsin period (Eyles and Eyles, 1983; Eyles and Westgate, 1987). Clast horizons are found **within** the lowermost diamict facies of the Sunnybrook and therefore are most likely to have formed in a subaqueous setting.

In summary, the proposed model for formation of clast horizons is a "two-step" process. The first step involves the emplacement of clasts in horizons in the substrate, either by clasts settling through lake bottom muds or by current winnowing of accumulated diamict. Neither of these processes are likely to have produced preferred orientations of clast a-axes. In the second step, clasts in horizons were preferentially aligned at select sites by seasonal lake ice, which affected a limited percentage of clast horizons, because only one of the three measured sites along the Bluffs showed a preferred orientation -- other horizons, which have random orientations of clast a-axes, were unaffected. Striae on a limited number of clasts may have been etched by seasonal lake ice during accumulation of the Sunnybrook or when clasts were affected by a previous subglacial event predating deposition of the Sunnybrook. And finally, because clast horizons are found only in the base of the Sunnybrook and at sites on the relative 'highs', it is concluded that the processes responsible for formation of clast horizons acted only during the beginning of the Sunnybrook interval, when lake depths would have been relatively shallow on the highs. Winnowing of lake bottom sediments and grounding of seasonal lake ice would not have been possible in 'channel' areas, where deeper glaciolacustrine conditions prevailed.

2.2 LAMINATED LITHOFACIES

The diamict facies of the Sunnybrook are closely associated with fine-grained laminated deposits. These laminated deposits occur as either thin units within diamict facies of the Sunnybrook (e.g. sections 9304, 9317, 9324, 9329; **Fig. 2.1**) or thicker successions (up to 24m) overlying the diamict where it infills lows on the Scarborough delta (e.g. sections 9303A, 9315; **Fig. 2.1**). Laminated deposits are of two types, either undisturbed (in original depositional position) or deformed (post-depositionally contorted or disturbed).

2.2.1 UNDISTURBED LAMINATED SEDIMENTS (Fl)

Thick units (up to 24m) of finely-laminated silty-clays and fine sands are identified at Dutch Church and Fishleigh sections at the Bluffs. Clark (1986) describes similar units along Duffins Creek, and in the Don Valley Brickyard. In each case, the fine-grained laminated facies overlie massive and stratified diamict facies which infill palaeotopographic lows cut into the underlying formations. The thicknesses of laminated units vary from 10 m (Duffins Creek: Clark, 1986) to 24m (this study), depending on the depth of the palaeotopographic low. The laminated facies described in this study have either been interpreted as part of the Lower Thorncliffe Formation (Karrow, 1967; Eyles and Clark, 1988a,b) or as part of the Sunnybrook (Karrow, 1969; Eyles and Eyles, 1983; Hicock and Dreimanis, 1992a). These laminated facies are thought to represent a "prodelta channel fill" (Eyles and Clark, 1988b) which preceded the progradation of the Thorncliffe delta. Dropstones and diamict clots in lower laminated facies are evidence for ice rafting by icebergs early in Thorncliffe time. In this study, fine-grained laminated facies are included as part of the Sunnybrook because of their intimate association (i.e. conformable contacts) with underlying diamicts.

Description

In the Dutch Church area (**Fig. 2.1a**) individual laminae within laminated facies commonly show progressive fining (grading), from fine sand to clay, and have variable thickness moving upsection. The thicknesses of laminae/beds change from <1 cm at the base, 2 to 6 cm (and up to 100 cm) in the middle (**Fig. 2.11B**), and <2.5 cm in the upper portion of the succession (**Fig. 2.11A**).

Near the base of the laminated succession at Dutch Church, laminae, containing many small pebbles and brecciated silt clasts, are locally deformed by dropstones and diamict clasts (**Fig. 2.12**). Laminae commonly grade from finely bedded silt to clay, with some laminae containing a thin (≈3mm) sand component at their base. Dropstones and diamict clasts are present only in laminae in the lower part of the succession, disappearing upsection (**Fig. 2.13**). Silt-clast breccia horizons of variable thickness (<0.5 to 3.5cm; **Fig. 2.14**) consist of concentrations of silt clasts and are finely bedded. Variability in the amount of silt clasts within individual beds distinguishes "matrix-supported breccias", in which a fine silt and clay matrix holds silt clasts in suspension, from "clast-supported breccias", where silt clasts are in contact with one another (**Fig. 2.14B**)

- the former being more common. Fine-grained laminated sediments are also inter-fingered with tongues of massive diamict toward the base of the succession at both Dutch Church and Bluffers Park sections (**Fig. 2.1a**). The diamict units have loaded into underlying fine-grained laminations causing some deformation of the laminae (**Fig. 2.14A**).

Greater sand bed frequency, coinciding with thicker laminations (up to 100 cm thick), is recorded moving upsection through fine-grained laminated facies (e.g. Dutch Church; **Fig. 2.13**). These upper laminae are often made up of gradations from rippled sand to silt and clay. Loading of sands into laminated beds, producing sand pillow structures (Sd facies), starved climbing rippled (Sr facies) and planar-bedded sands (Sp facies) are found in upper portions of the succession (**Fig. 2.15**). Sr and Sp sand beds have **sharp** bases and bioturbated tops. Bioturbation structures, such as gently curving and looping traces, are common on bedding plane surfaces throughout the succession, with a steady increase in trace-fossil abundance upward through the laminated succession (described in Clark, 1986). Some very thin sand beds are almost indistinguishable due to complete bioturbation (**Fig. 2.15A**). Thick massive beds (coded as Fm in the middle of the succession) are predominantly silt/clay and contain stringers of fine sand and horizons of silt clast breccia (**Fig. 2.13**).

In addition to laminated channel fill sequences, undisturbed laminated facies are found **within** both stratified and massive diamict facies of the Sunnybrook exposed in the creeks. A pair of laterally extensive interbedded silt

Figure 2.11: A) Finely laminated silts and clays in upper laminated facies at the Dutch Church (section 9303A; **Fig. 2.1a**). Beds are 0.5-1.5cm thick on average and contain occasional beds of fine sand. These facies are interpreted as turbidites (likely C-D-E divisions of the Bouma sequence: **Fig. 2.17**). Knife handle is 9cm. **B)** Transition from fine (1-2cm), in the lowest laminated facies, to thick (2-6cm) rhythmites moving upsection at the Dutch Church (section 9303A; **Fig. 2.1a**). Transition point is located at the head of the ice axe (length 80cm).

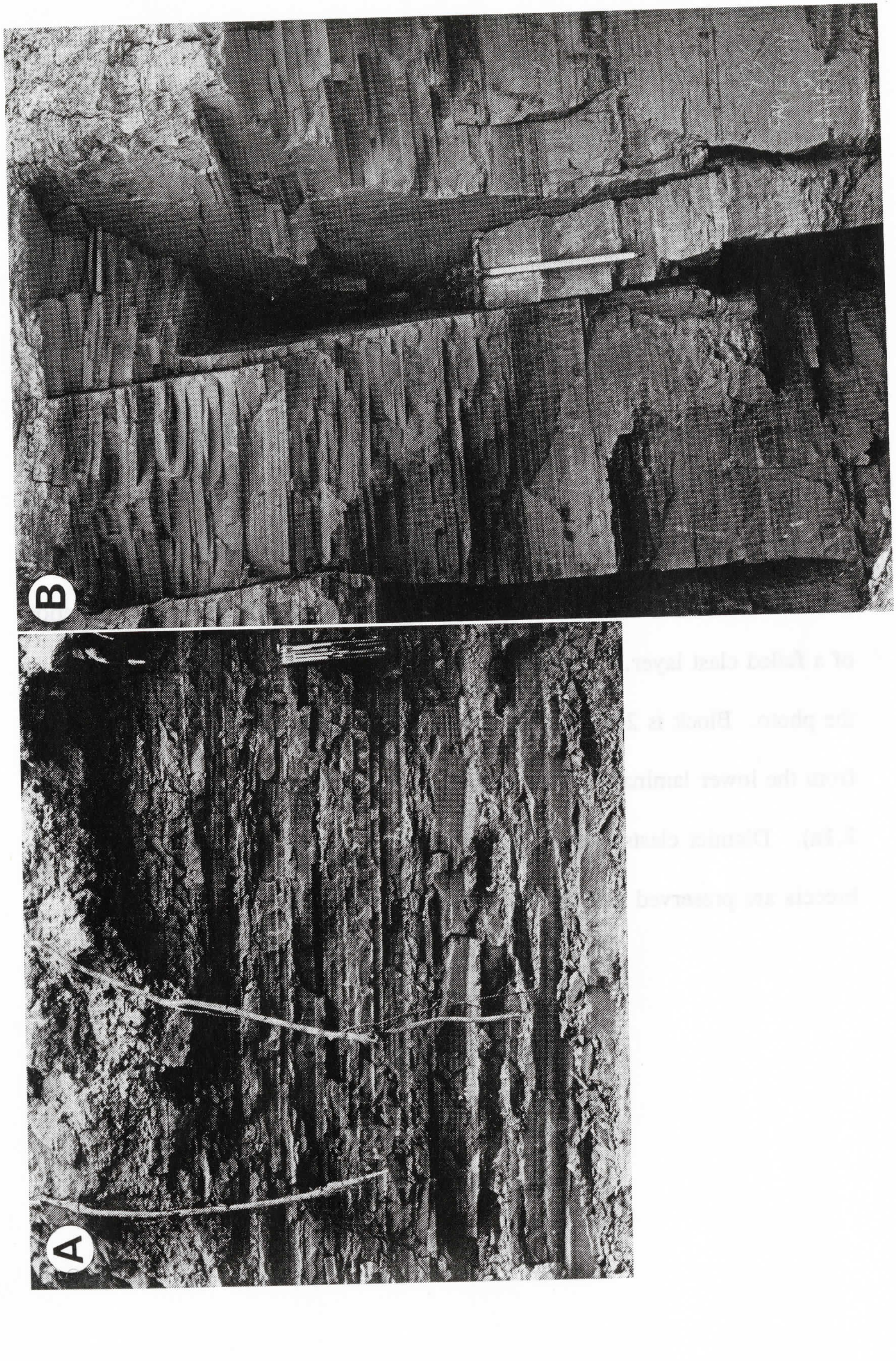
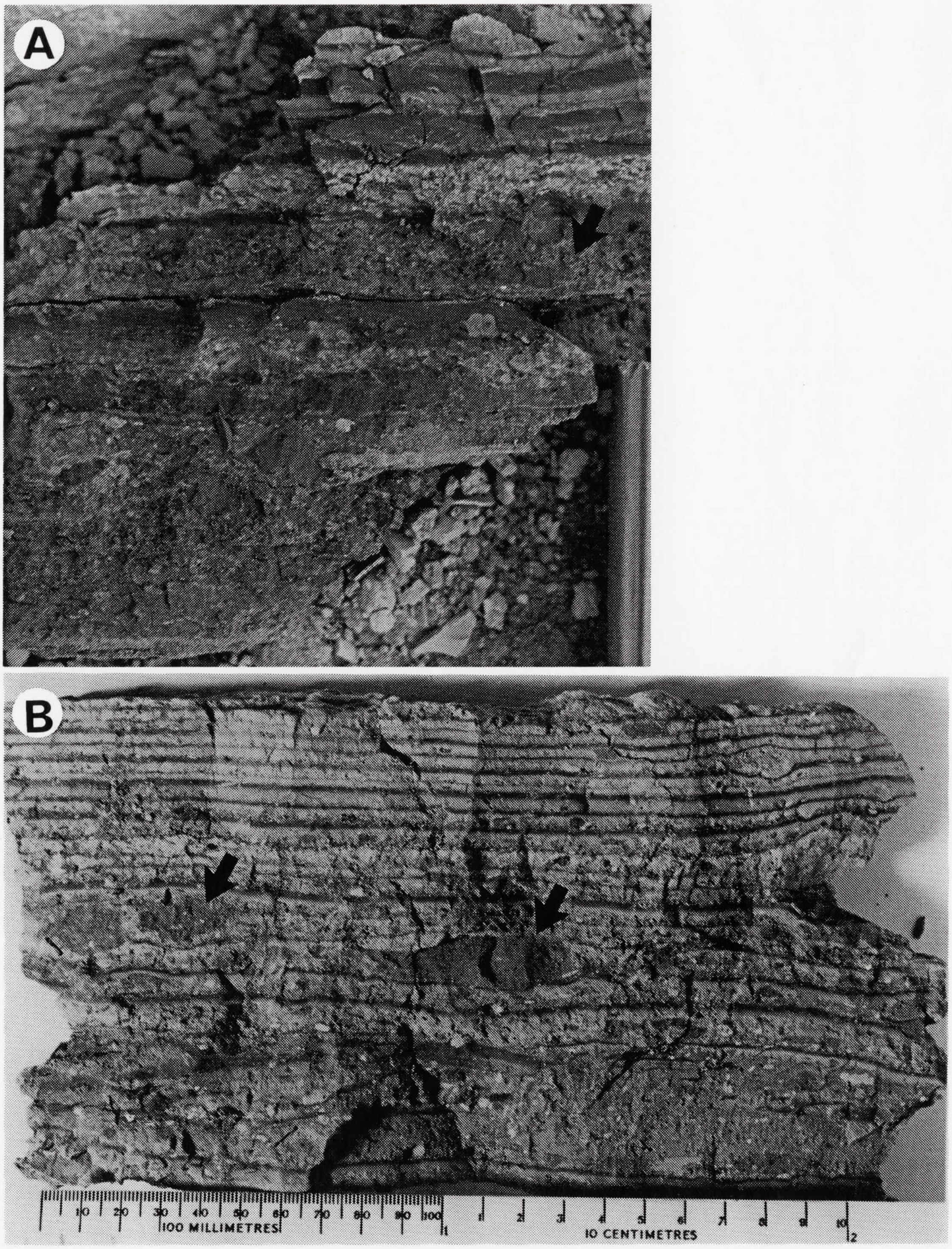

A
B

Figure 2.12: A) Laminated beds of brecciated silt and diamict clasts and clay. Brecciated silt and diamict clasts probably originate by slumping of pre-existing beds and suggest sediment instability in the basin (west of Dutch Church, section 9303A). A bed rich in granular-sized stones (arrowed) indicates the introduction of a failed clast layer. Large pieces of diamict are visible in the lower third of the photo. Block is 20cm top to bottom. **B)** Block of laminated silts and clays from the lower laminated facies west of the Dutch Church section (9303A; **Fig. 2.1a**). Diamict clasts (arrowed; several cm's long) and horizons of silt clast breccia are preserved within these laminated beds.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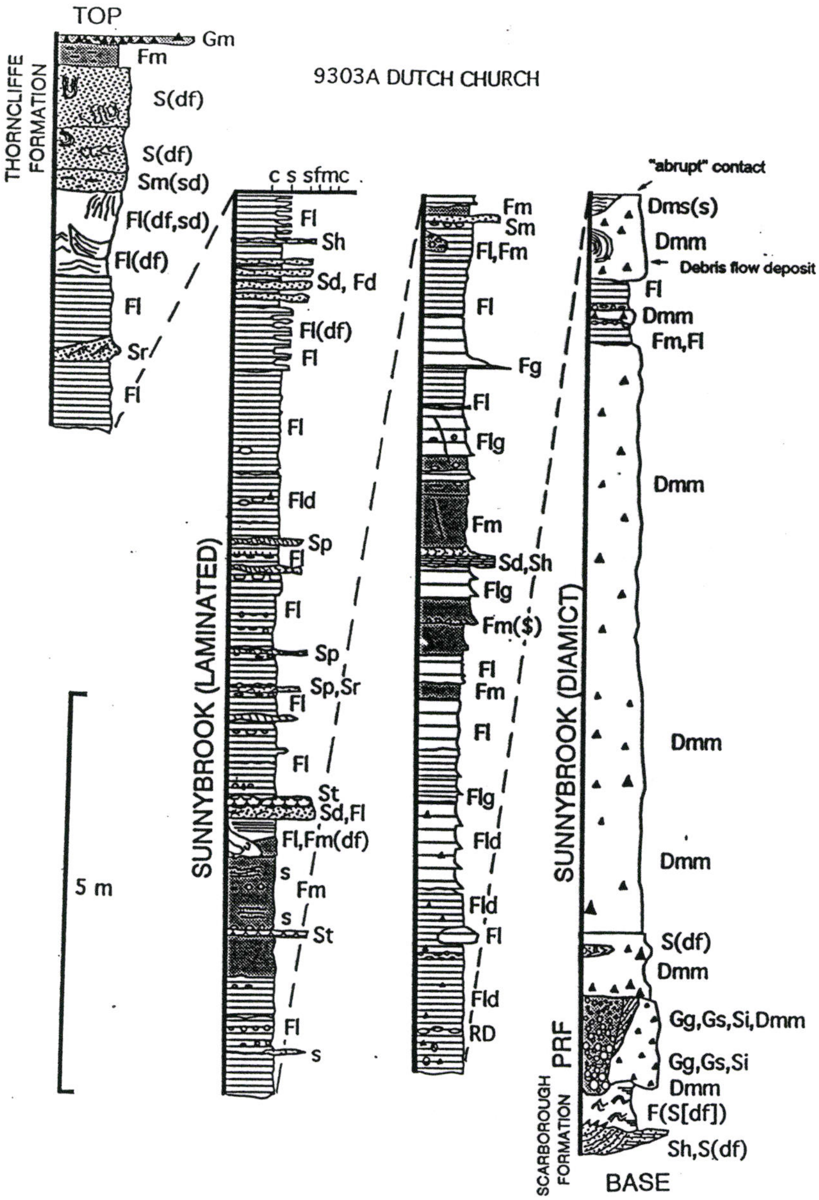
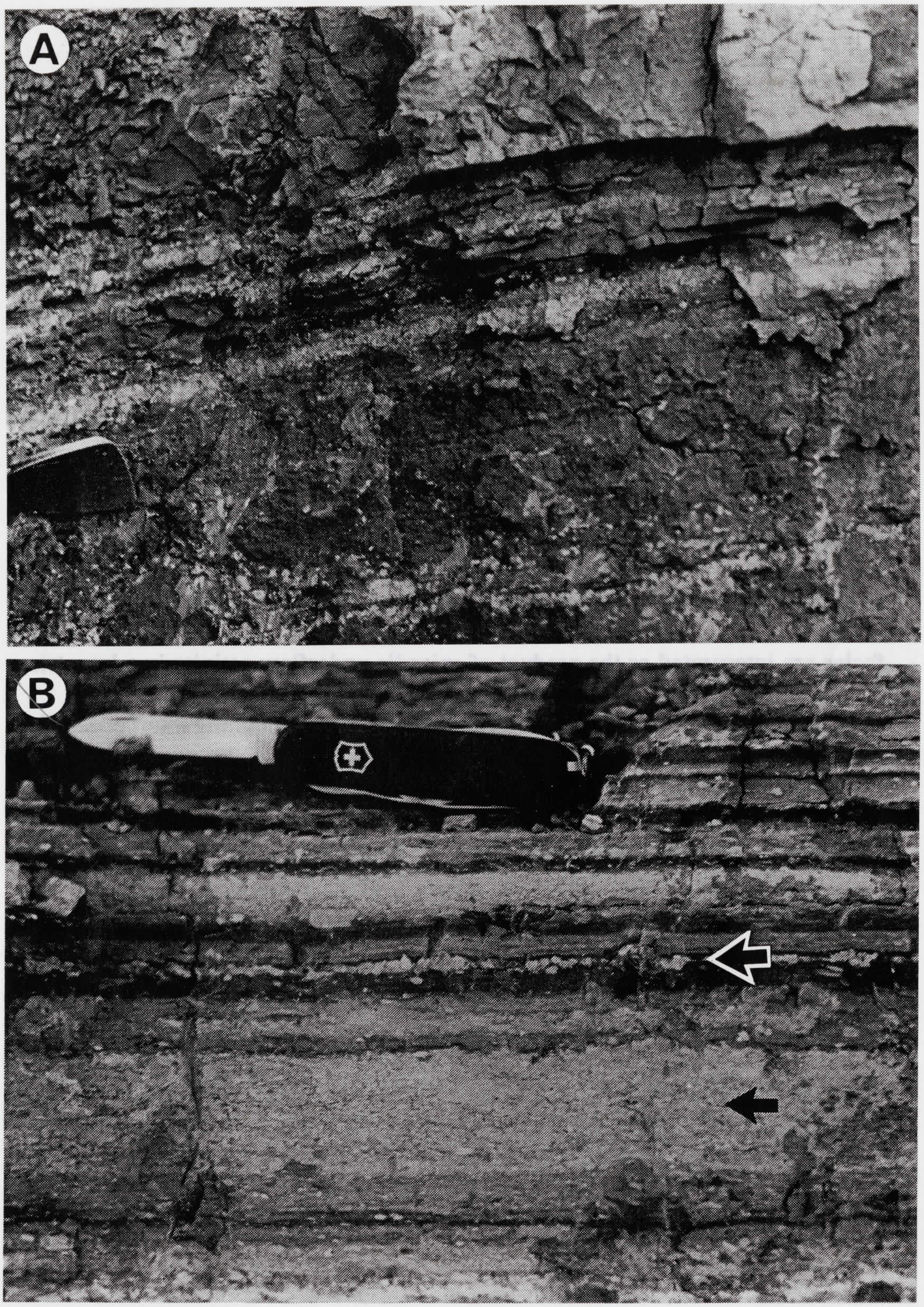


Figure 2.13: Log 9303A within the Dutch Church channel at Scarborough Bluffs. Diamict is fine-grained and predominantly massive; lowermost portions of the diamict include some sand lenses. A large debris flow is represented by the 1m thick bed of massive diamict at the top of the right hand column. Basal contact of the diamict with deformed Pottery Road Formation (PRF) gravels is sharp. Upper portions of the log are laminated facies of Sunnybrook with variable thicknesses of graded turbidite beds. The contact between massive and laminated facies is abrupt (arrowed); however, diamict rafts/clasts (RD) and silt clast breccia are included in lower laminated facies which suggest the continued influence of icebergs and slumping during deposition of the lowermost laminated facies. Note that the frequency of dropstones in laminated facies (Fld) decreases upsection. For lithofacies code see **Fig. 1.11.**

Figure 2.14: Silt clast breccia underlying a large debris flow deposit in the Dutch Church Channel. **A)** Interbedded horizons of silt clast breccia (light coloured) and clay at the top of a 30cm thick unit of laminated facies at the Bluffers Park (section 9303B; **Fig. 2.1a**). These laminated facies are overlain by a bed of massive and stratified diamict, thought to represent a large debris flow deposit at Bluffers Park section (blade of ice axe at left hand side of photo is 5cm long). **B)** Interbedded silt clast breccia and clay underlying a massive diamict unit interpreted as a debris flow deposit at the Dutch Church (section 9303A; **Fig. 2.1a**). This photo is taken of the same unit as the photo in A). Both matrix- (upper arrow) and clast-supported (lower arrow) breccias are shown here. Knife handle is 9cm long.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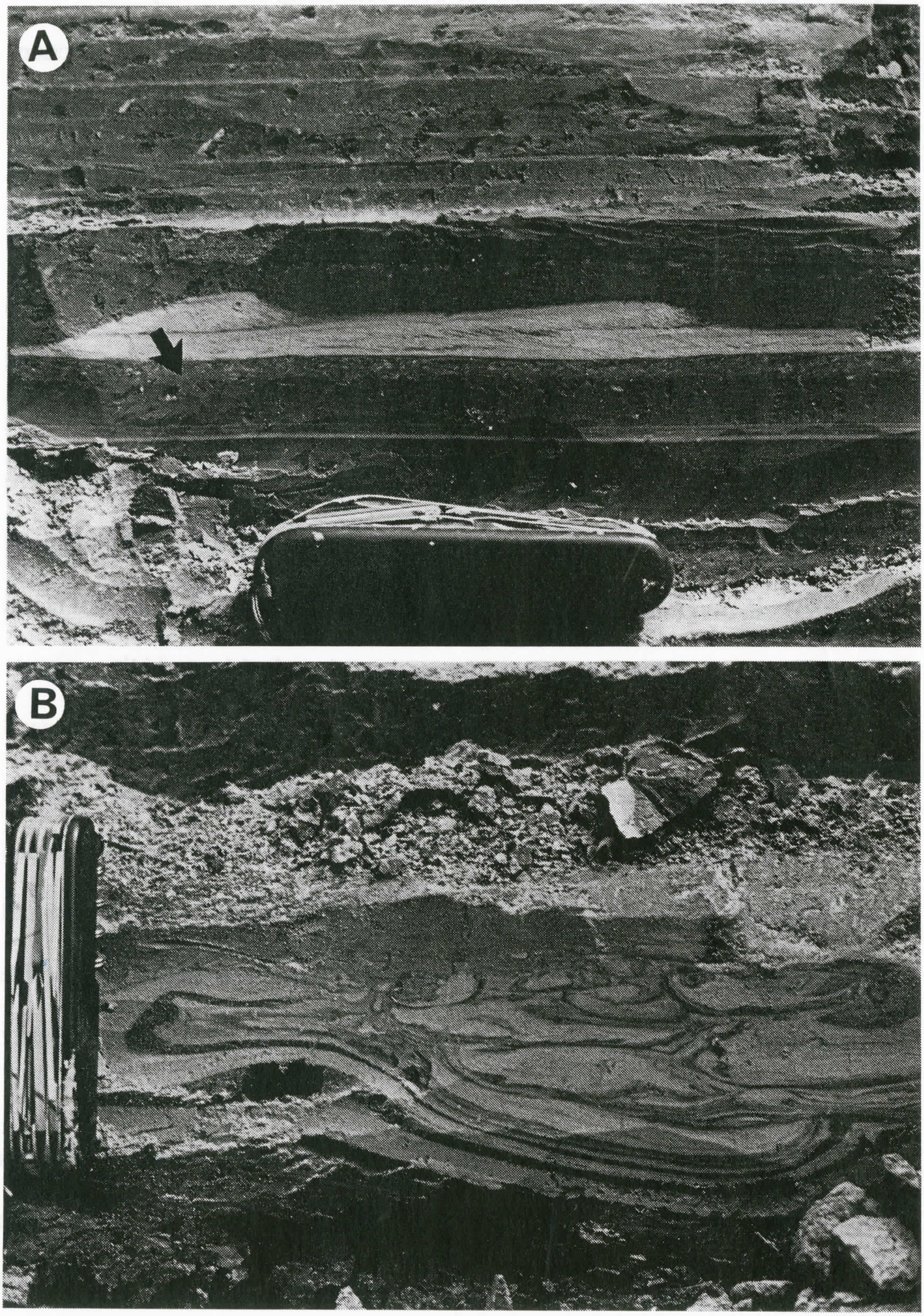
Figures 2.15: A) Interbedded fine sand, silt and clay within upper laminated facies at Dutch Church (section 9303A; **Fig. 2.1a**). Light-coloured beds are rippled fine sand ("starved climbing ripples"). Mottling in muds above and below sand beds (arrowed) is evidence of bioturbation. Knife handle is 9cm. These facies are interpreted as the product of episodic underflow activity in a lacustrine environment. **B)** Soft sediment deformation structure containing interbedded fine sand and mud within laminated facies (section 9303A; **Fig. 2.1a**). This probably formed as a slump or loading feature and shows abundant de-watering structures. Knife handle is 9cm.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clast breccia and clay beds - traced for over 10m along the outcrop - was found within massive diamict facies at Rouge site 9324 **(Fig. 2.16)**. At this section, undisturbed homogeneous beds of clay form sharp contacts with underlying silt clast breccia horizons and overlying massive diamict. Silt clast breccia horizons show a gradational contact with underlying massive diamict facies. These undisturbed beds within diamict facies have important implications for the inferred origin for the diamict.

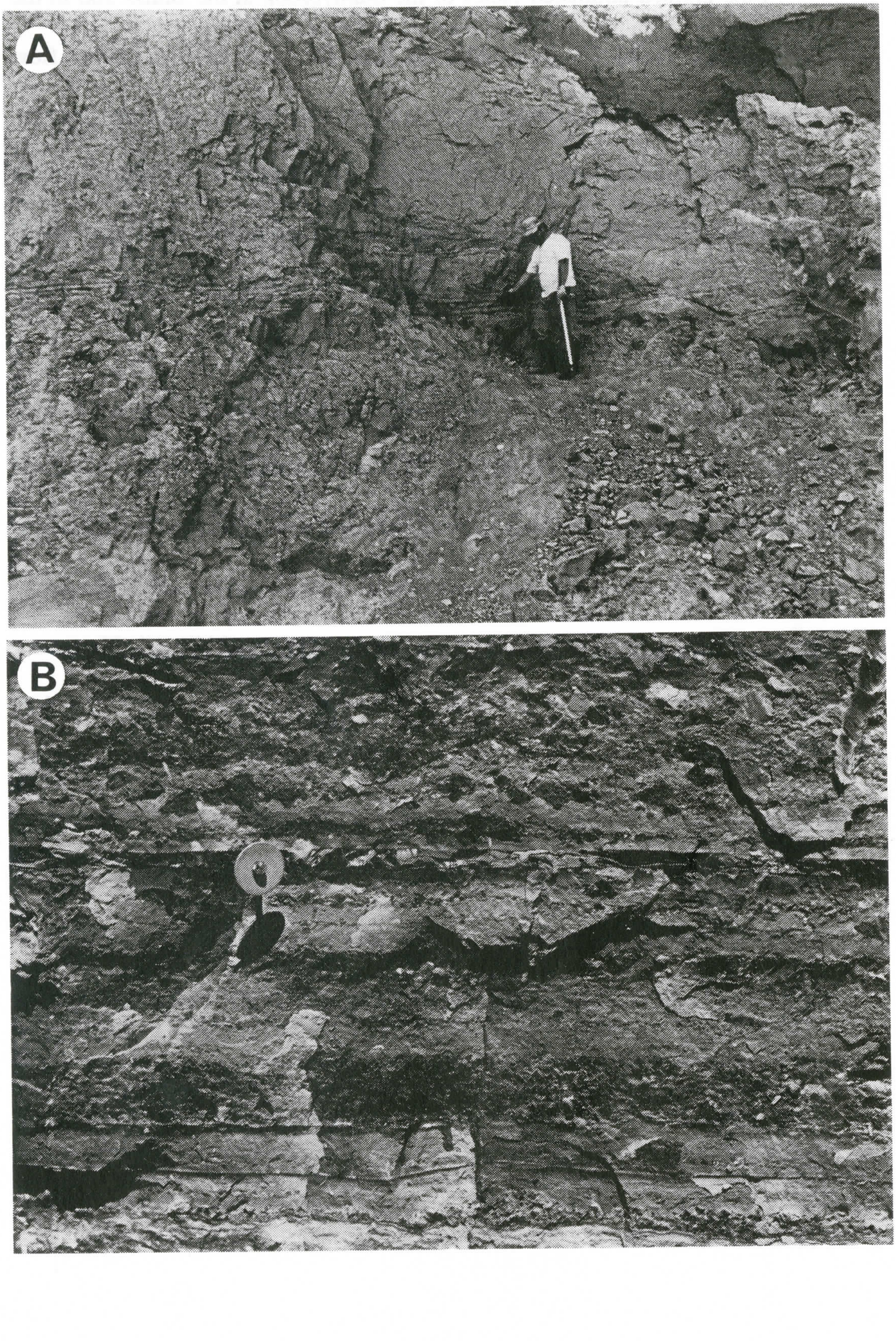
Interpretation

Laminated fine-grained sediments form in subaqueous environments where sediment supply and energy conditions vary temporally, allowing systematic variations in the grain size of accumulating sediment. Grading in laminated facies is most often found in fine-grained successions deposited by turbidity currents (turbulent subaqueous sediment gravity flows) and by density underflows (quasi-continuous density-driven currents) in both glaciomarine (Cowan and Powell, 1990; Phillips and Smith, 1992; Walker, 1992b) and glaciolacustrine environments (Mathews, 1956; Gustavson, 1975; Harrison, 1975; Eyles and Eyles, 1992). The abundance of graded beds within the laminations of the Sunnybrook suggests an origin from both turbidity currents and density underflows.

A turbidite is the "event bed" deposited by a turbidity current, which is defined as a "density current, driven by gravity acting on the density difference between the current and surrounding water" (Walker, 1992b, p.239). Individual turbidites can spread over large areas producing fine laminations and are the primary means to transport sediments into low energy, deep-water environments (Walker, 1992b). Turbidity currents commonly begin as short-travelled slumps often on steep subaqueous slopes and thus they are frequently documented in close proximity to active deltas (Syvitski and Farrow, 1989; Kostachuk et al, 1992; Phillips and Smith, 1992), where fluvially-derived sediments provide ample material to be carried away from the delta into the basin. Turbidity currents may be triggered by a number of different mechanisms including: failure of over-steepened depositional slopes (Mathews, 1956; Kostachuk and McCann, 1987; Syvitski and Farrow, 1989; Phillips and Smith, 1992), rapid deposition and overloading of delta foresets causing subaqueous failures (Kostachuk et al., 1992; Phillips and Smith, 1992), seismic shock (Walker, 1992b), and storm wave liquefaction of near-shore slopes causing failure (Walker, 1984).

Density underflows are similar to turbidity currents except that the density difference is caused by contrasts in water temperature or in suspended sediment content of the current with surrounding environment. For example, cold glacially-derived, silt-laden meltwaters upon entering a lake, will sink below the warmer lake water and generate bottom currents and may lead to slumps and currents on the delta front (Mathews, 1956; Smith and Ashley, 1985). Density underflows do not travel as far as turbidity currents as they rapidly lose their density with distance travelled, however, the sediment products of density underflows closely resemble those of turbidity currents.

Figure 2.16: A) Laterally extensive ($\approx$10m) laminated silt clast breccia and clay beds (to left of figure) within Sunnybrook (Dmm facies) exposed along Rouge River (section 9324; **Fig. 2.1b**). These sediments have been offset by a major fault to the right of the figure with a vertical throw of 35cm. The faulting postdates Sunnybrook deposition as overlying Thorncliffe formation deposits are also affected (Thorncliffe sand is the dark (wet) unit in the top right corner of the photo). **B)** Close up of finely interbedded silt clast breccia and clay (nail penetrates one clay bed) shown in a); silt clast breccia probably results from subaqueous slumping, clay beds represent periods of quiet deposition in a lacustrine environment.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Fine-grained laminated facies of the Sunnybrook at the Bluffs and in the Duffins Creek Valley are interpreted as lacustrine sedimentary gravity flow deposits. Silts and sands, probably brought into the lake by meltwater streams and deposited on delta slopes, were resedimented downslope by turbidity currents and/or density underflows forming graded beds of fine-grained sediment. More buoyant clay settled out from suspension between turbidity current events, producing thin clay laminae.

Turbidites are usually described by the Bouma succession **(Fig. 2.17)**, with individual elements of a graded bed classified as A through E divisions, based on the relative abundance of coarse-grained material and of sediment deposition. Turbidites in the lower portion of the Dutch Church section (9303A) likely represent D-E divisions of the Bouma sequence; upper turbidites (with greater sand presence) represent C-D-E divisions. An increasing thickness of individual laminae moving upwards at the Dutch Church section **(Fig. 2.1a)** is interpreted as an increase in the magnitude of turbidity currents while the increasing coarsening of the individual laminae, moving upsection, suggests a more proximal sediment source. These are caused by increasing sediment volumes delivered by meltwater streams to a slumping delta front and may reflect the progradation of the delta into the basin and/or reductions in water depth.

Coincident with upsection changes in laminae thickness and sand content, are changes in the degree of bioturbation on bedding plane surfaces. Longer and longer return periods, between turbidite/density underflow events, are suggested

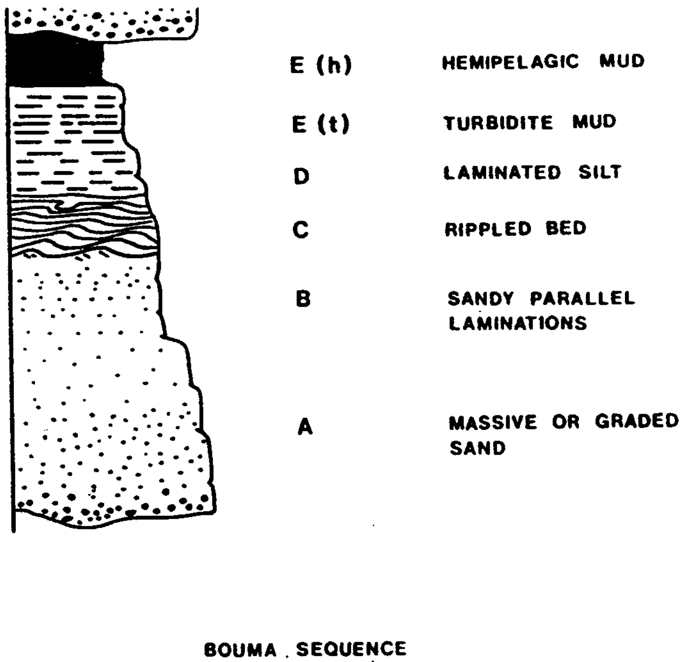

Figure 2.17: Classic turbidite Bouma sequence showing five distinct divisions produced during passage of a turbidity current. More distal turbidity currents exhibit only the C,D,E and D,E divisions. (From Walker, 1984).

by increasing evidence of bioturbation in laminae moving upsection (e.g. at Dutch Church, section 9303A; Clark, 1986). A high frequency of these events would severely limit or preclude bioturbation. Bioturbated tops of individual sand beds, found in upper fine-grained facies (**Fig. 2.15A**) suggest a period of subaqueous exposure. Infrequent, rather than continuous, turbidity current and density underflow activity is inferred.

Fine-grained laminated sediments of the Sunnybrook show an intimate relationship with underlying diamict facies. Dropstones and diamict clasts within the lowest laminated facies suggest the continued presence of floating ice and/or icebergs in the Lake Ontario basin during the earliest stages of laminated facies deposition (Eyles and Eyles, 1983; Thomas and Connell, 1985). The slopes of subaqueous channels, in which laminated facies were accumulating, were probably unstable. The occurrence of several large debris flows (represented by massive diamicts; **Fig. 2.1a**) within the lowermost fine-grained laminated units gives evidence of this instability. The loss of dropstones and debris flow facies moving upwards within the laminated facies (e.g. Dutch Church, Bluffers Park and Fishleigh sections; **Fig. 2.1a**), suggests a reduction in ice volume in the Lake Ontario basin during the latest phases of Sunnybrook deposition. Ice retreat from the basin margins most likely led to the re-establishment of a subaerial drainage network, and the development of broad delta fronts around the margins of the Lake Ontario basin during Thorncliffe Formation time.

Fine-grained laminated facies of the Sunnybrook were initially identified as varves (Antevs, 1928; Coleman, 1932; Karrow, 1967), indicative of seasonally-controlled sedimentation patterns. However, the common occurrence of silt clast breccia layers within laminae, diamict interbeds, and frequent evidence of slumping (Lajtai, 1969; Eyles, C.H., 1982; Clark, 1986; this study), suggest that laminated facies at the Bluffs are not the product of seasonally controlled sedimentation. Rather they represent aperiodic sediment gravity flow events focused into topographical lows (i.e. debris flows, turbidity currents and density underflows). Silt clasts within fine-grained laminated facies represent "rip-up" clasts eroded from underlying beds during subaqueous resedimentation (Eyles et al., 1983), or were formed by the disaggregation of previously-deposited beds during slumping. Similar successions of graded laminae are interpreted as turbidite successions in Pleistocene lakes (Harrison, 1975; Teller, 1976; Shaw and Archer, 1978) and in modern glacial lakes (Mathews, 1956).

Fine-grained laminated facies that occur <u>within</u> massive diamicts (**Fig. 2.16**) represent periods when little or no ice rafting of clasts and coarse debris occurred. Silt clast breccia, interbedded with intact clay beds within massive diamict, are the result of subaqueous slumping. Intact clay beds may represent the fine-grained 'tail' of the slump which created the breccia layer and interrupted the diamict accumulation. Most importantly, the presence of these undisturbed laminae within massive diamict beds adds further support for a subaqueous origin of the Sunnybrook diamict facies (see section 2.1).

2.2.2. DEFORMED LAMINATED SEDIMENTS - Fl(df)

Description

Deformed laminated facies, consisting of contorted lacustrine sediments, are found within upper diamict and laminated facies at the Bluffs and throughout the Sunnybrook outcropping in the dissecting creeks (**Figs. 2.1** and **2.5**). Laminated sediments are deformed to varying degrees in all outcrop areas, but, recognition of individual graded silt and clay beds is still possible. Deformation structures, observed at the Bluffs and in the creeks, include both large and small scale deformation features. These structures include "carpet" folding and s-folds (**Fig. 2.18**) and flow noses (**Fig. 2.7**). Large scale folds have amplitudes of $\approx$1m (**Fig. 2.18A**) whereas small scale folds have amplitudes of $\approx$5cm (**Fig. 2.18B**). In most instances, individual silt beds within these folds remain unbroken, and are traceable laterally across the section. Deformed laminated silts and clays, which appear to have flowed downslope (**Fig. 2.7**), are restricted to upper portions of predominantly massive diamict facies.

In several outcrops along the Rouge and Duffins Creeks the Sunnybrook forms the modern stream bed because of its resistance to erosion (**Fig. 2.19**). Subtle deformation structures, readily visible due to erosion of the sediment by flowing water, include s-folds (**Fig. 2.18B**) and flow features (**Fig. 2.7B**) in graded silt and clay beds. The palaeoflow directions of six flow nose structures within deformed laminated facies, seen in plan view along the Rouge River (**Fig. 2.7B**; section 9308A and 9308B), were measured. These palaeoflows had a mean

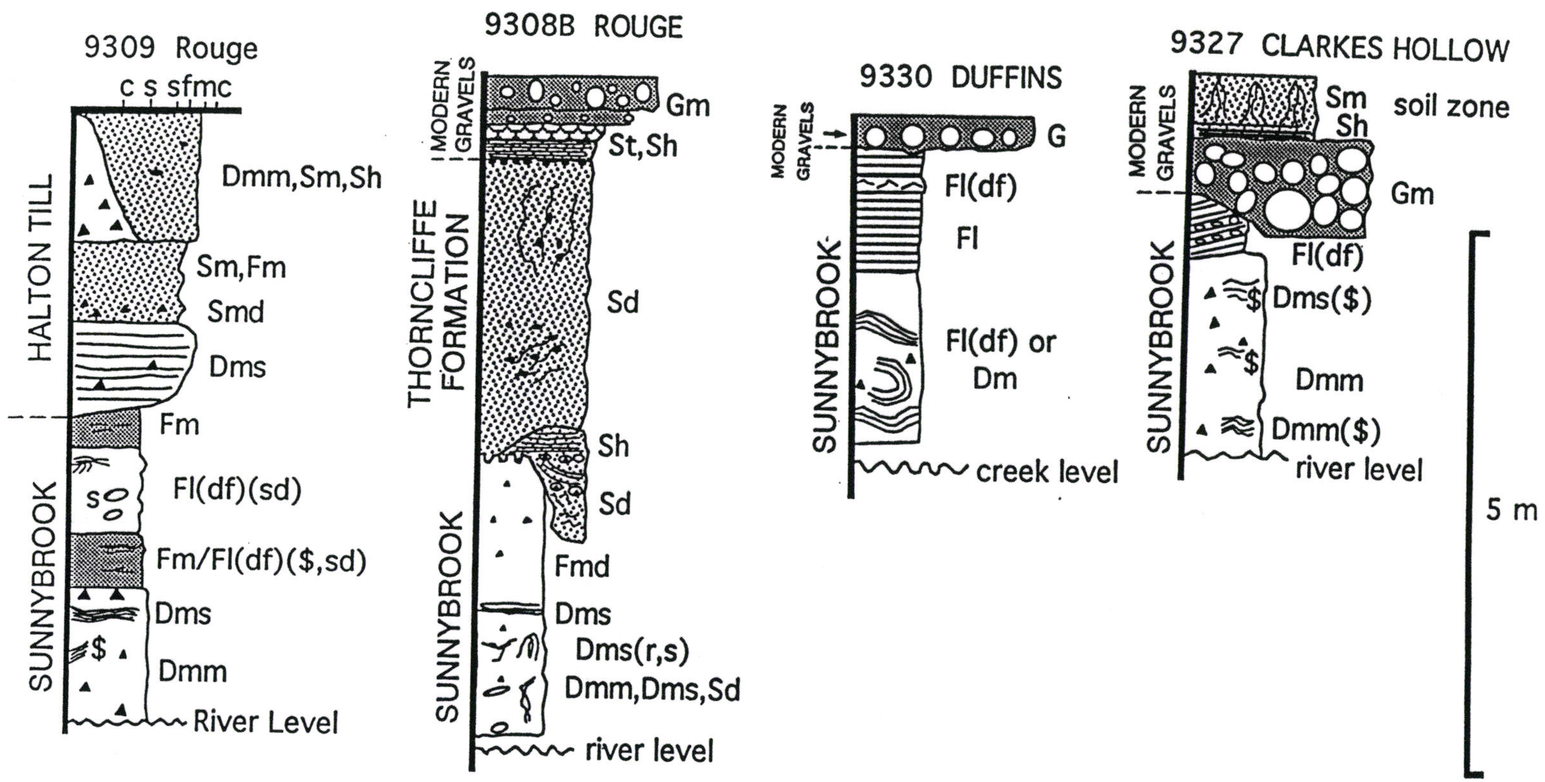

Figure 2.19: Logs show Fl(df) facies of Sunnybrook exposed in the dissecting creeks. Creek sections have a greater proportion of deformed laminated sediments than Bluff sections.

Figure 2.18: Soft sediment deformation features in fine-grained laminated facies (Fl(df)). **A)** Contorted beds of laminated muds with interbedded silt and fine sand beds/lenses which have been preferentially removed by modern fluvial erosion. Ice axe handle is 80cm long. Rouge section 9308A (**Fig. 2.1b**). **B)** Close-up view of small "s-type" fold shown in A); dark cavities were once occupied by silt and fine sand beds or lenses. Knife handle is 9cm long. **C)** S-type fold within laminated facies at Fishleigh Drive (section 9315; **Fig. 2.1a**). These structures probably result from interbedded fine sand and muds slumping short distances downslope. Knife handle is 9cm long. **D)** "Carpet" folding in deformed laminated facies within diamict of the upper Sunnybrook at Sylvan Park. Laminated beds are graded from silt to clay; no clasts are present. Material has been deformed by slumping. An arrow points to a plane along which this slump failure has occurred. Knife handle is 9cm long.

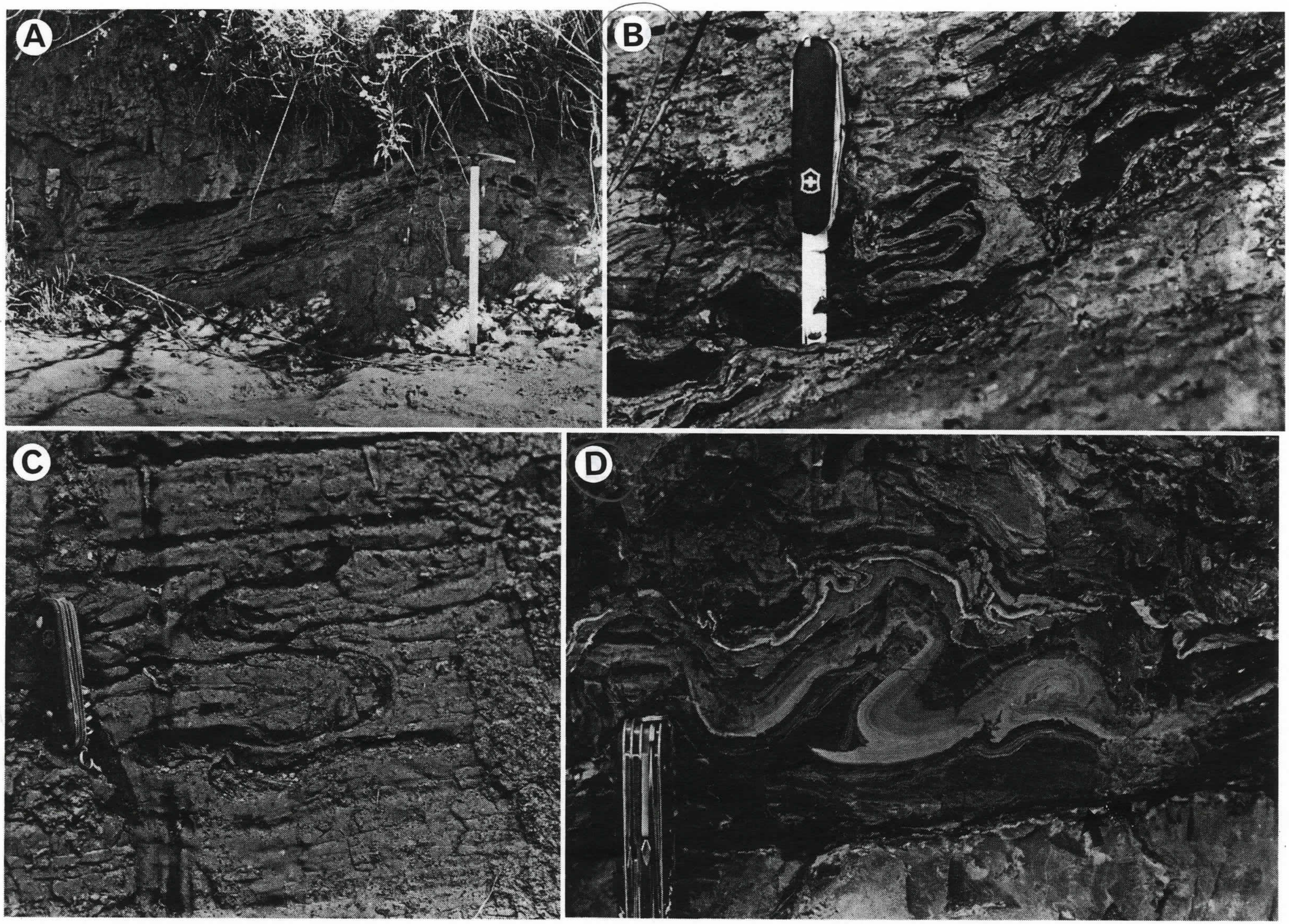
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Figure 2.20: A) Gently undulating laminated silts and clays overlying fine-grained Sunnybrook diamict along Duffins Creek. These beds are laterally extensive and traceable to other sections in the immediate area. **B)** Moving several metres to the right of the previous photo, the Fl beds are deformed to a vertical position. Folding is quite intense but localized (Duffins section 9329; **Fig. 2.1c**).

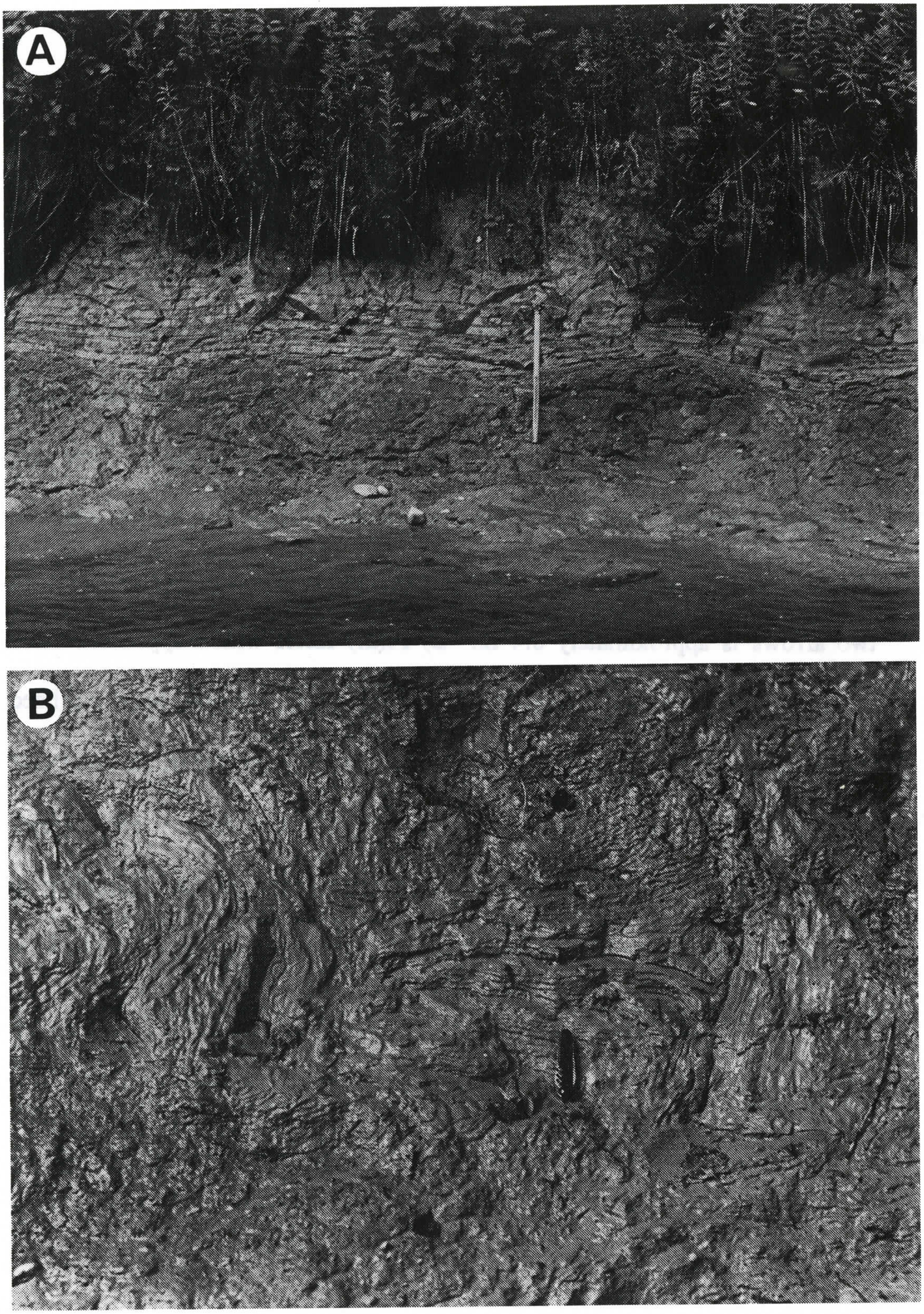
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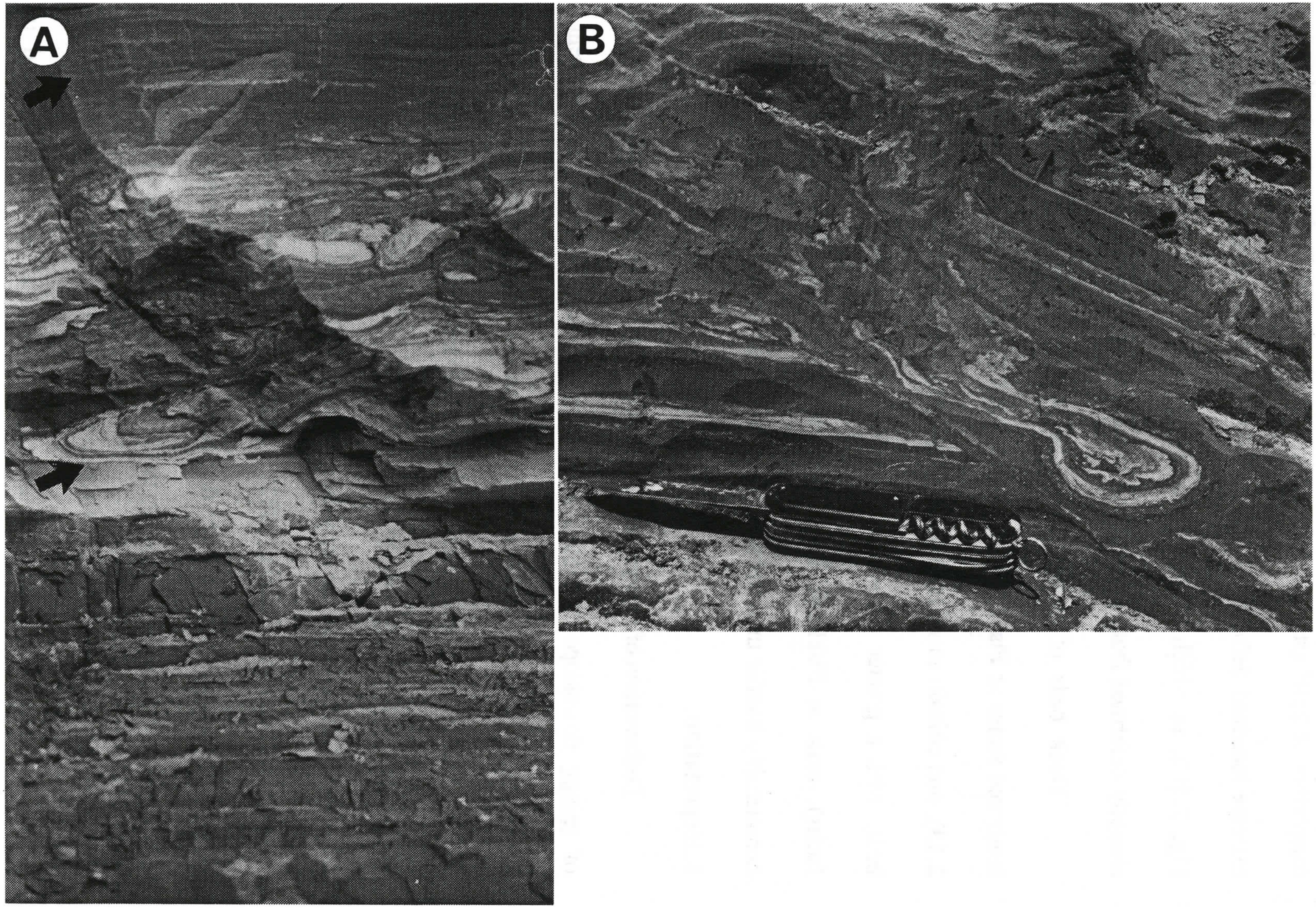
Figure 2.21: A) Deformed laminated facies Fl(df) at Fishleigh Drive (section 9315; **Fig. 2.1a**) showing resedimented (slumped) laminated silt and clay -- light coloured beds are silt. The contact between disturbed laminated beds and undisturbed graded rhythmites beneath is marked by the lower arrow, which is the low-gradient plane along which the slump travelled. Distance between the two arrows is approximately 0.4 m. **B)** Fl(df) facies within upper laminated facies at Dutch Church (section 9303A; **Fig. 2.1a**), showing very localized displacement of graded beds of silt and clay. Slide plane (failure surface) cuts diagonally across the photo from upper left to lower right -- undeformed sediments to left and deformed to the right of the slide plane. Direction of slumping, identified by the tongue outlined by the light-coloured silt beds, is to the right. Knife handle is 9cm.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orientation of 210° (standard deviation = 26°). In the Duffins Creek Valley, extreme localized deformation of laminated facies was observed (section 9329; **Fig. 2.1C**), in which laterally extensive laminated beds of silt and clay are abruptly deformed from a horizontal to vertical position (**Fig. 2.20**).

Thick beds of massive mud, up to 1.5m thick, occur within upper laminated facies at Fishleigh Drive and Dutch Church sections (**Figs. 2.1a and 2.13**), and contain small pockets of folded and contorted silt stringers. Similar beds, with a greater proportion of deformed silt stringers (logged as Fl(df) facies), exist at Fishleigh Drive (section 9315) where Fm and Fl(df) beds conformably overlie undisturbed graded laminated facies (**Fig. 2.21**).

Interpretation

Deformation of fine-grained laminated facies probably occurred as a result of **minor** downslope slumping and sliding in a subaqueous environment. Gravitational processes cause sediment deformation as a result of frictional drag forces. These forces are generated by flowing and sliding of debris masses on the substrate (slumping), and by sediment loading of the substrate. The original sediment character may or may not be preserved in a slump ('coherent' vs 'incoherent' slumps of Mills, 1983). Sedimentary structures observed in the Sunnybrook suggest a range in the degree of deformation of laminated facies. In short-travelled subaqueous slumps, laminated silt and clay beds will show minor deformation, which includes the s-type and carpet folds, with individual bedding preserved, observed within the uppermost diamict along the Bluffs and in outcrops along the Rouge River (**Fig. 2.18**). More intense, and probably longer travelled, slumps produced 'tongues' of laminated fine-grained sediments which flowed downgradient (**Figs. 2.21A** and **2.7**); paleoflow data recorded for flow noses records the paleoslope orientation (210°) at the time of deformation of the laminated facies. The most rigorous slumping, recorded within the Sunnybrook's facies caused rafts of laminated sediments to become disassociated from their original sedimentary facies (**Fig. 2.3D**). Long distance transport of beds results in the formation of brecciated beds, with silt beds broken up into small angular fragments. These silt clast breccia horizons are associated with the occurrence of turbidity currents, which were discussed in detail in section 2.2.1.

In summary, the majority of deformation of fine-grained facies in the Sunnybrook is best attributed to short-distance slumping and sliding of subaqeuous sediments. This interpretation of the cause of deformation is consistent with other features of the Sunnybrook such as the occurrence of thick packages of fine-grained turbidites, thin debris flow deposits, and flow noses within massive diamict facies (Eyles and Eyles, 1983) that also suggest sediment instability in the basin.

2.3 CONTACTS WITH UNDER- AND OVER- LYING FORMATIONS

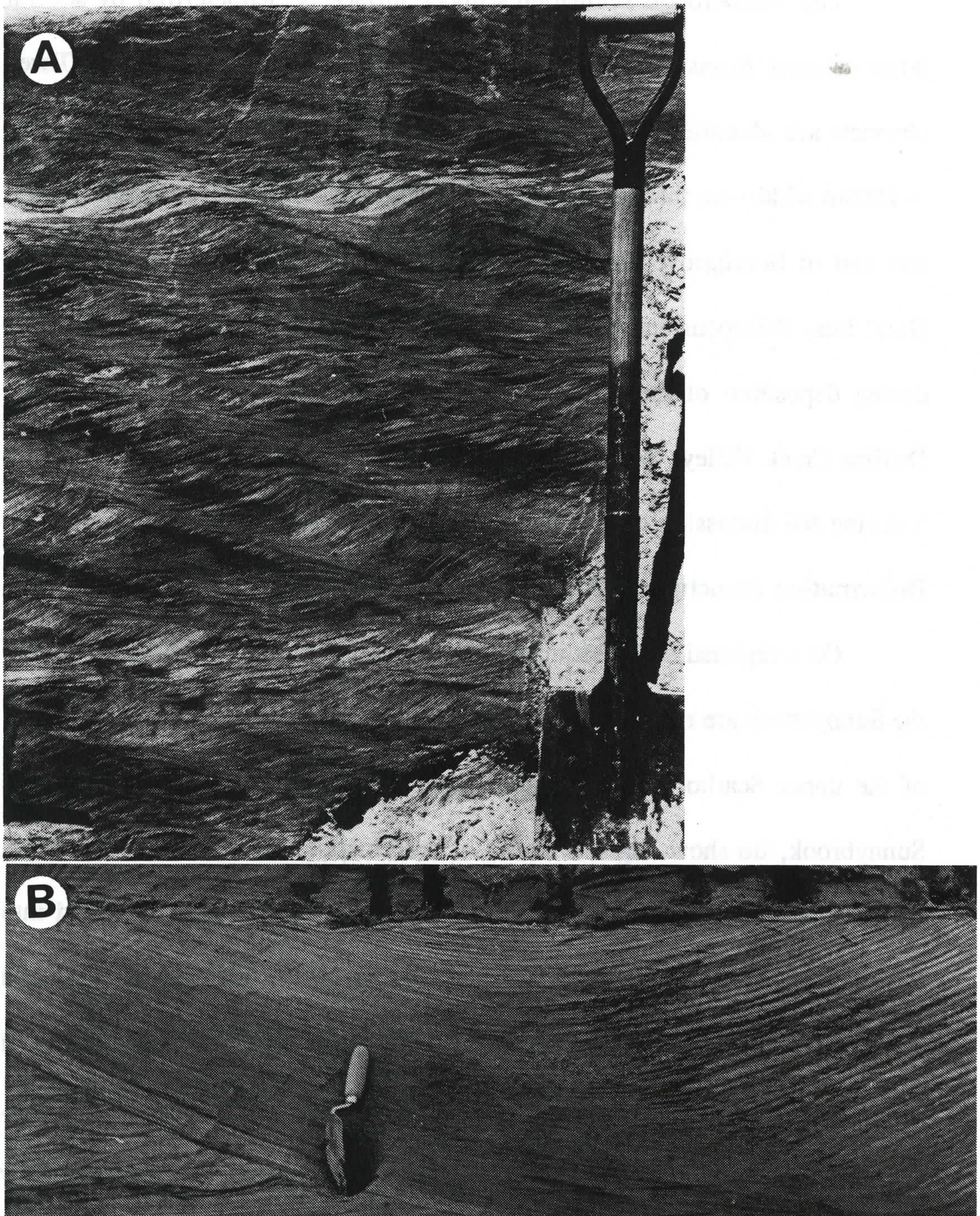
2.3.1. SCARBOROUGH FORMATION

The importance of the contact between the Sunnybrook diamict and the Scarborough Formation is to document the change in environmental conditions from dominantly sand deposition, in upper Scarborough sediments, to diamict deposition of the lowermost Sunnybrook.

The Scarborough Formation is interpreted as a delta, deposited in a large high-level lake during early Wisconsin time (Karrow, 1967). It is characterized by a coarsening upward sequence, passing from laminated prodelta muds, through delta foreslope/foreshore sand/muds, into a sandy braided fluvial complex (Clark, 1986). The upper Scarborough Formation has distinctive sedimentary structures including rippled (ripple-drift cross lamination) and channelized sands **(Fig. 2.22)** and has a high organic matter (peat) content. Dominant facies types identified in the upper Scarborough Formation in this study include horizontally bedded sands (Sh) and sequences of rippled sands (Sr) **(Fig. 2.1a)**. Sh facies are characterized by flat-lying, horizontal sand laminae, less than 0.5cm thick -- laminae are delineated by concentrations of heavy mineral grains (Clark, 1986). Climbing ripple facies (Sr facies) are finely bedded and include foreset drapes of organic material **(Fig. 2.22A)**.

The coarsening upwards trend in the Scarborough Formation reflects a transition from relatively quiet water deposits (prodelta) to sediments deposited in progressively higher energy conditions (delta top; Clark, 1986). Cross- and planar bedded sands (St and Sp facies) at the top of the coarsening upwards succession represent the top-set beds of the Scarborough Delta, which were deposited in a fluvial environment. Overlying these St and Sp sands are stacked sequences of climbing ripples (Sr facies) - in the upper Scarborough - which may be attributed to deposition by repeated density underflows in a subaqueous setting (c.f. Shaw, 1975; Thomas, 1984; Ashley et al., 1985). Climbing ripples can be formed by traction currents or in association with turbidites and represent times of high suspended sediment supply (Eyles, C.H. et al., 1993). Large amounts of peat washed into the lake during this time, drape the ripple forms **(Fig. 2.22A)**. Variations in current energies are recorded by thin horizontally laminated sands (Sh facies) erosively overlying current ripples. Sh facies indicate either high velocity currents producing upper flow regime plane bed conditions (Harms et al., 1982 fide Clark, 1986), or deposition from relatively low velocity traction currents (Eyles, C.H. et al., 1993). The former seems more likely because Sh facies of the upper Scarborough often contain mud chips - presumably re-worked lake floor sediments - and form an erosional contact with underlying Sr facies. A decrease in current velocity results in lower flow regime current ripple migration (Sr facies). The implication of this change from fluvial (St and Sp facies) to subaqueous depositional processes (Sr and St facies) is the inference that the top of the Scarborough Delta was **flooded** immediately preceding the deposition of the Sunnybrook diamict.

Figure 2.22: A) Rippled muddy sand (ripple-drift cross stratification) of the upper Scarborough Formation, outcropping along the Rouge River (section 9324; **Fig. 2.1b**). This photo shows undeformed Scarborough sediments 0.6m below the Sunnybrook's basal contact. Dark colouring on ripple foresets is organic material(peat fragments). Shovel length is 105cm. **B)** Channel form filled with planar cross-bedded and low angle inclined sands within upper Scarborough Formation at Hi section (9325; **Fig. 2.1a**). The channel truncates horizontally laminated and ripple cross-bedded sands below. Dark beds are rich in organic material. The top of this feature is located 1.5m beneath the basal contact of the Sunnybrook drift. Trowel is 25 cm long.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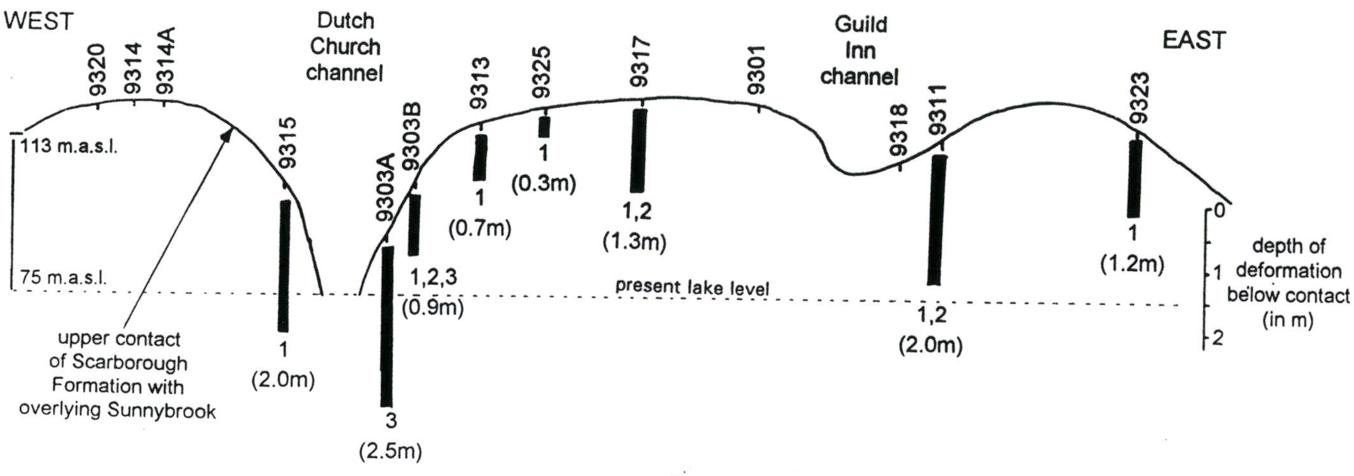
The Scarborough Formation's upper surface is characterized by several large channel forms over which the Sunnybrook Formation drapes. Three channels are identified along the Bluffs (**Fig. 1.2**); two channels ($\approx$53m deep, $\approx$1500m width) cut through the entire Scarborough Formation at Dutch Church and east of Beechgrove Drive and the other ($\approx$16m deep, $\approx$1750m width) at Guild Inn. Palaeocurrents measured by Clark (1986) indicate southeasterly flow during deposition of the Scarborough Formation along the Bluffs and in the Duffins Creek Valley. More detail concerning these channels follows in chapter 3 during the discussion of the Sunnybrook's facies associations.

Deformation Structures Within Upper Scarborough Formation

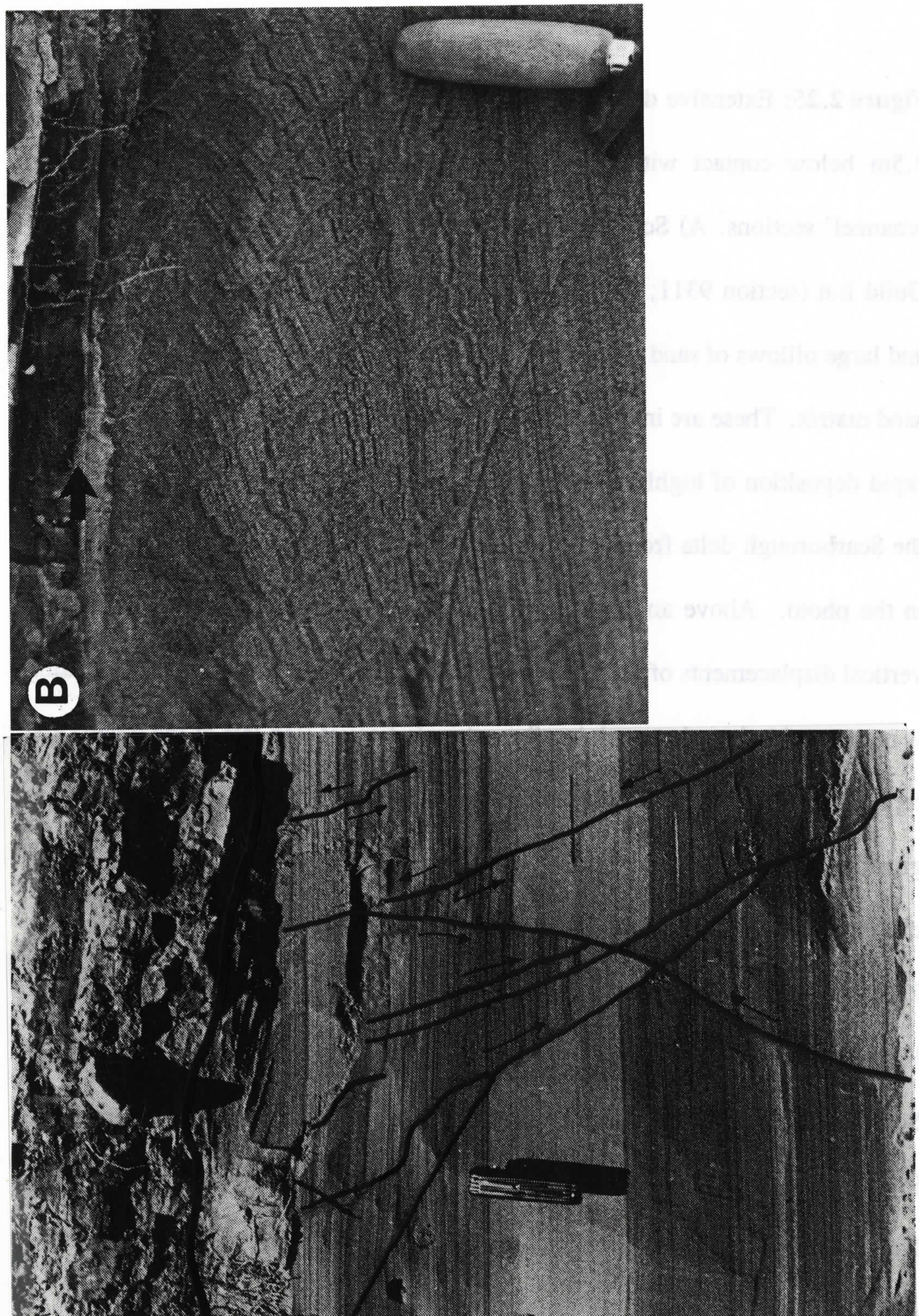
On a regional scale, sediments of the Scarborough Formation underlying the Sunnybrook are remarkably undeformed. However, in places, the sediments of the upper Scarborough Formation immediately below the contact with the Sunnybrook, do show slight evidence of deformation. Deformation structures within Scarborough sediments vary along the Bluffs, and may be classified into three types: (1) high angle faulting (9315, 9303B, 9313, 9325, 9317, 9311 and 9323; **Fig. 2.23**); (2) sub-horizontal or low angle faulting (9303B, 9317 and 9311; **Fig. 2.23**); and (3) loading structures (sections 9303A and 9303B; **Fig. 2.23**). The type and magnitude of deformation is controlled, to some extent, by the section's position in relation to channels and highs along the Scarborough / Sunnybrook contact (**Fig. 2.23**) but overall is very slight. The depth of deformation affecting the Scarborough Formation is less on the highs (0.0m to



- the magnitude of deformation is represented by solid bars below site number and by the numbers in parentheses below bar (0.3m)
- the type of deformation within the upper Scarborough Formation is indicated at each site below the bar:
  1= high angle faulting; 2= low angle faulting; 3= loading structures

Figure 2.23: Types and locations of faulting and loading deformation in the upper Scarborough Formation along the Scarborough Bluffs. The depth of deformation in the Scarborough below contact with the overlying Sunnybrook is indicated by the vertical bar below each section number; as well, the types (1, 2, or 3) of deformation and depth of deformation are written below each bar. No deformation in the upper Scarborough Formation was recorded at sections 9320, 9314, 9314A, 9301 or 9318.

Figure 2.24: Deformed Scarborough sediments underlying the Sunnybrook on the "highs". **A)** High angle faulting at the top of the Scarborough Formation at Morningside Ave (section 9323; **Fig. 2.1a**). Overlay sketch shows positions of fault planes and interpreted relative movements along faults. Basal contact of the Sunnybrook (marked with heavy line on overlay) is sharp and undulating and is not affected by the faulting, which suggests that the deformation occurred prior to the deposition of the Sunnybrook. Knife handle is 9cm long. **B)** Micro-faulting within upper Scarborough Formation sediments at Morningside Ave (section 9323; **Fig. 2.1a**). The downward extent of faulting is marked by the line cutting diagonally from centre left to bottom right of the photo. Photo was taken $\approx$1m to the right of **Fig 2.24A**. Sharp horizontal contact with the Sunnybrook is arrowed.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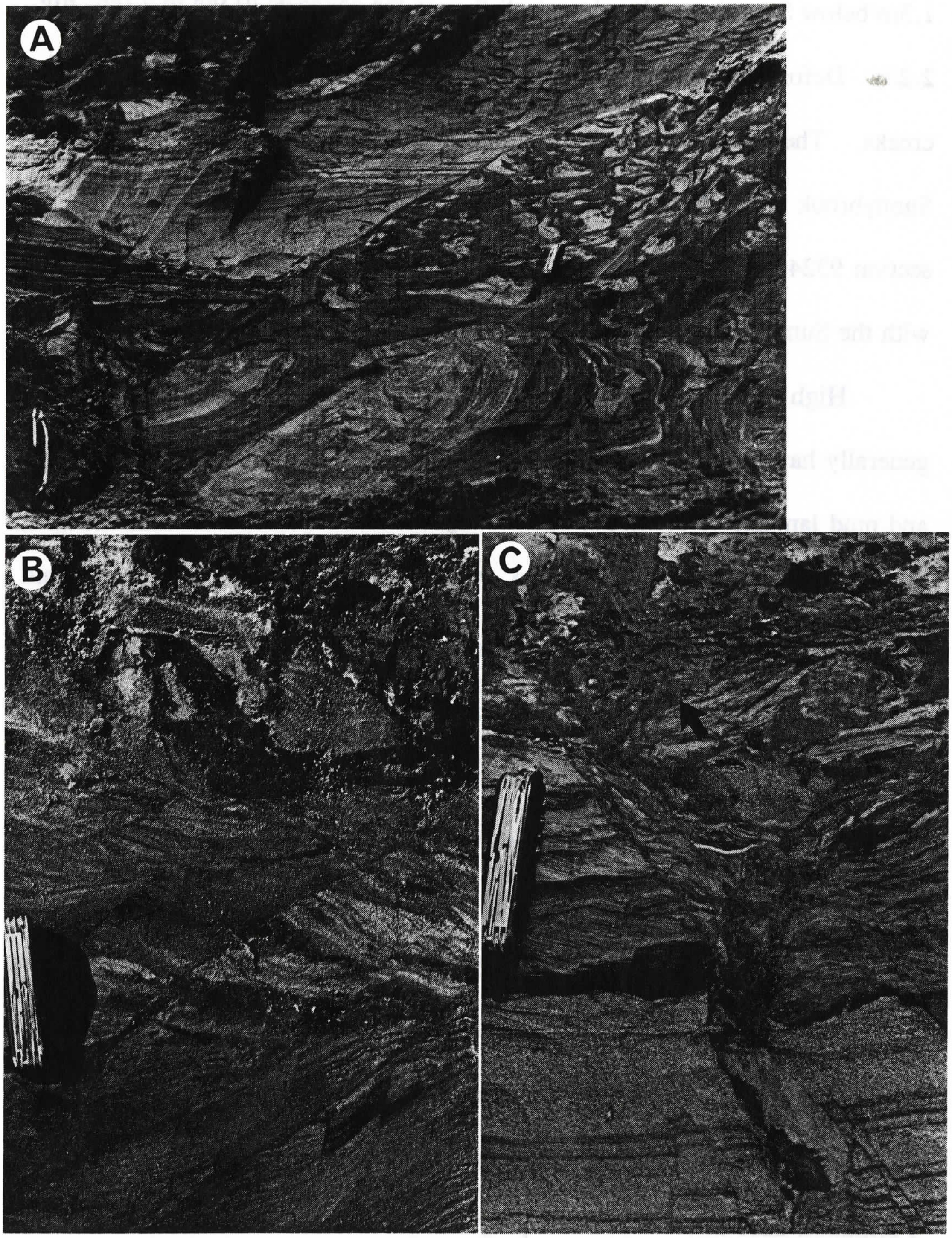
A

Figure 2.25: Extensive deformation of Scarborough Formation sediments (up to 2.5m below contact with the Sunnybrook) at Dutch Church and Guild Inn 'channel' sections. **A)** Scarborough Formation below the Sunnybrook contact at Guild Inn (section 9311; **Fig. 2.1a**). On the right side of the photo, both small and large pillows of sand (containing organic material) form rafts within a muddy sand matrix. These are interpreted as syndepositional deformation associated with rapid deposition of highly water saturated Scarborough Formation sediments on the Scarborough delta front. A large fault is traced from bottom left to top right in the photo. Above and left of the fault, a series of small faults have caused vertical displacements of horizontally bedded sands (Sh). This high angle faulting is not traceable into the overlying Sunnybrook diamict (top left of the photo) and represents a second phase of Scarborough deformation which may be related to growth faulting on the prograding delta. **B)** Deformed and faulted sand within the top of the Scarborough Formation at Fishleigh Drive (section 9315; **Fig. 2.1a**). Darker horizons are organic-rich and show several off-setting faults. Knife handle is 9cm long. **C)** Water escape structure within top part of Scarborough Formation (at section 9311; **Fig. 2.1a**). The feature is not traceable into Sunnybrook facies (contact arrowed) and likely predates Sunnybrook time. Note high angle faulting associated with margins of dewatering structure at base of photograph.



A
B
C

1.3m below Sunnybrook basal contact) than in the channels (0.9m to 2.0m; **Fig. 2.23**). Deformation structures were not common below the Sunnybrook in the creeks. The depth of deformation of the Scarborough Formation below the Sunnybrook in the Rouge Valley (sections 9324 and 9326) is less than 0.7m. At section 9324, rippled muddy sand beds, lying approximately 1m below contact with the Sunnybrook (**Fig. 2.22A**) are undeformed.

High angle faults are described as those with dips greater than 40°. These generally have small displacements (<5 cm in vertical displacment) of the sand and mud laminae of the upper Scarborough Formation (**Fig. 2.24A**) or show a microfaulting character (**Fig. 2.24B**). The depth that high faulting extends into the upper Scarborough Formation is commonly less than one metre on the relative highs along the Bluffs; in the channel areas, however, the deformation extends up to 2.5 m below contact with the overlying Sunnybrook (**Fig. 2.23**). High angle faulting of the uppermost Scarborough is associated with de-watering structures (**Fig. 2.25C**).

Preservation of beds displaced by high angle faulting within the Scarborough (**Figs. 2.24** and **2.25C**) suggests these sediments were de-watered and subjected to 'brittle' deformation processes, rather than 'plastic' deformation. Neither faulting nor related de-watering structures within the upper Scarborough Formation have affected the overlying Sunnybrook which suggests that faulting and de-watering pre-dated deposition of the Sunnybrook (**Fig. 2.24**). The minor degree of high angle faulting deformation, limited to the upper Scarborough

Formation, suggests 'passive' emplacement of the overlying Sunnybrook facies. It is likely that high angle faults and microfaulting were caused by compaction as the sediments de-watered, or in response to vertical loading.

Rare sub-horizontal low angle faults occur in the Scarborough Formation below the Sunnybrook, (sections 9303B, 9317 and 9311: **Fig. 2.23**). Low angle faults are those with dips less than 40° and have produced greater displacements (in excess of several 10's of cm) of the laminae of the Scarborough Formation than high angle faults. The depth of deformation attributed to low angle faulting can reach approximately two metres below contact with the Sunnybrook and is greatest in channel areas (**Fig. 2.23**). For example, a large fault in the Scarborough Formation, dipping at approximately 35°, divides high angle faulted Sh facies from organic-rich sand pillows loaded into a muddy sand matrix (**Fig. 2.25A**); both syndepositional loading deformation and postdepositional faulting appear to have operated at this site. At the Cudia Park section (9317; **Fig. 2.1a**), an extensively deformed layer (about 0.5m thick) of Sr facies overlies Sh facies which contain some high angle faults. Similar to the high angle faulting, none of these low angle faults affected the Sunnybrook immediately overlying the faults.

Low angle faulting indicates a greater influence of lateral, rather than vertical stresses in producing the deformation structures observed in the upper Scarborough Formation. As well, the more extensive and intensive deformation of the upper Scarborough Formation sediments found along channel sides (sections 9315, 9303B, and 9311; **Fig. 2.23**) suggests a more vigorous 'deforming mechanism' in these areas. Small and large pillows of sand, identified alongside a low angle fault in the Guild Inn channel (**Fig. 2.25A**), are believed to have formed at the same time as the channels themselves. Hence, a significant proportion of deformation identified in channels is probably related to the formation of these channels as part of distributary channel network in a prograding delta.

The final type of deformation in the uppermost Scarborough Formation is ascribed to loading, and is related to the presence of the Pottery Road Formation (PRF; described in section 2.3.2). This loading deformation is present only in channels along the Bluffs. Loading into the underlying Scarborough Formation during deposition of the PRF, caused the extensive deformation of the uppermost Scarborough Formation at Dutch Church and Bluffers Park (sections 9303A and 9303B; **Figs. 2.23** and **2.26C**; see discussion of PRF below).

2.3.2 POTTERY ROAD FORMATION

The Pottery Road Formation (PRF) is the formal stratigraphic name given to a series of channelized gravels and coarse-grained sands that occur in places between the Scarborough Formation and Sunnybrook diamict. The PRF was first documented by Karrow (1967) with a type section in the Don Valley Brickyard (**Fig. 1.1**); current outcrop of PRF in the study area is limited to exposures of channelized pockets of gravel and sand along the Bluffs at Dutch Church, Bluffers

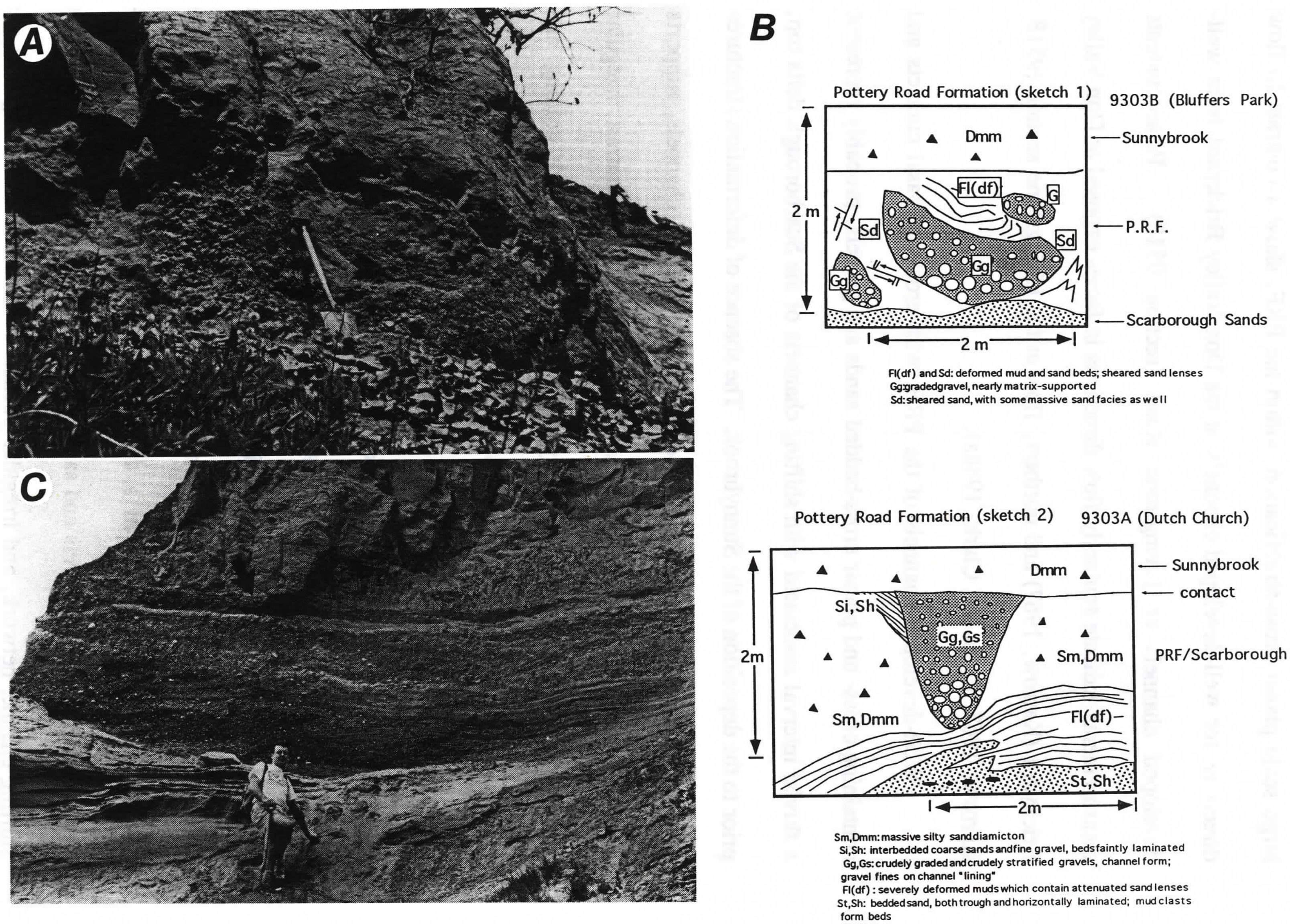
Park and Livingstone Road (sections 9303A, 9303B and 9318; **Fig. 2.1a**). Sediments of the PRF are found only in channels cut into the underlying Scarborough Formation, and not on the relative highs, along the Bluffs.

Sediments ascribed to the PRF along the Bluffs consist of graded gravels and coarse-grained sands occurring either in channels or irregular pockets (**Fig. 2.26**). Channel form is both well-developed (section 9318; **Fig. 2.26C**) and crude (section 9303B; **Figs. 2.26A,B**). Sediments within well-developed channels tend to be better organized (e.g. multiple sets of cross-bedded and horizontally bedded coarse sands and gravels; section 9318; **Fig. 2.26C**) than those within crude channels or irregular pockets. These irregular pockets (or 'crude channels') show weak grading and stratification, and are loaded into massive and deformed sands of the underlying Scarborough Formation (**Fig. 2.26B**). Scarborough Formation facies adjacent to PRF sediments may be either deformed - either by faulting or loading (**Fig. 2.26B**) - or undeformed (**Fig. 2.26C**). PRF loaded into sands caused small shear planes within sands (Sd; **Fig. 2.26B - sketch 1**) and mild deformation of underlying fine-grained laminated facies (Fl(df); **Fig. 2.26B - sketch 2**). At the Livingstone section (9318), no deformation of the Scarborough sediments was observed (**Fig. 2.26C**).

The contact of the PRF with the underlying Scarborough Formation shows a marked relief and is commonly erosive (Eyles and Clark, 1988a), evidenced by rip-up clasts of silty clay within gravels along the contact. Palaeocurrent measurements compiled by Karrow (1967) and Clark and Eyles (1988a), from

Figure 2.26: Photo and sketches of the Pottery Road Formation (PRF).

A) Crudely-developed channels (or irregular pocket) of PRF facies within the Dutch Church channel at Bluffers Park (section 9303B; **Fig. 2.1a**). Gravels show weak grading and a crude channelized form (e.g. pocket). Loading of PRF into the underlying Scarborough Formation has caused localized deformation of Scarborough sediments. Sketch 1 (in **Fig. 2.26B**) is a sedimentological representation of facies shown in this photo. Shovel is 1m tall. **B)** Sketches highlighting the sedimentological character of two crudely developed channels or irregular pockets of the PRF, from the Dutch Church channel (sections 9303A and 9303B; **Fig. 2.1a**). Text below each sketch describes the observed facies. Grading and stratification with PRF facies here are weakly developed; deformation of the Scarborough Formation here has been caused by loading of the PRF. **C)** Cross-bedded (trough and planar cross beds) and horizontally bedded coarse sands and gravels within the N-S oriented channel at Livingstone Road (section 9318; **Fig. 2.1a**). Cross-bedding indicates palaeocurrent flow to the north. Lower Sunnybrook diamict overlies this unit with a planar contact (arrowed).


A
B
C
Pottery Road Formation (sketch 1)
9303B (Bluffers Park)
Dmm
Sunnybrook
Fl(df)
G
Sd
Gg
P.R.F.
Scarborough Sands
2 m
2 m
Fl(df) and Sd: deformed mud and sand beds; sheared sand lenses
Gg:gradedgravel, nearly matrix-supported
Sd:sheared sand, with some massive sand facies as well
Pottery Road Formation (sketch 2)
9303A (Dutch Church)
Dmm
Sunnybrook
contact
Si,Sh
Gg,Gs
Sm,Dmm
PRF/Scarborough
Sm,Dmm
Fl(df)
St,Sh
2m
2m
Sm,Dmm: massive silty sanddiamicton
Si,Sh: interbedded coarse sands andfine gravel, bedsfaintly laminated
Gg,Gs: crudely graded and crudely stratified gravels, channel form; gravel fines on channel "lining"
Fl(df) : severely deformed muds which contain attenuated sand lenses
St,Sh: bedded sand, both trough and horizontally laminated; mud clasts form beds

large scale planar cross-stratification within the PRF, show a contrast in flow directions for well-developed channels in the Don Valley Brickyard from well-developed channels at Livingstone Road (section 9318). Palaeocurrents measurements indicate southerly flow directions in facies exposed at Don Valley Brickyard (Karrow, 1967) and northerly flow at the Livingstone section (9318; Karrow, 1967; Eyles and Clark, 1988a).

Well-developed channels of the PRF, with erosional basal contacts and containing cross- and planar cross-bedded sands and gravels, probably represent a fluvial interval associated with shifting channels of the Scarborough delta top, prior to the deposition of the Sunnybrook. The absence of deformation structures within the Scarborough Formation, beneath well-developed channels, supports these as in situ channels which dissected the deltaic sands. In contrast, irregular pockets of sand and gravel (crudely channelized), with weak grading and deformation in the underlying Scarborough Formation (Dutch Church and Bluffers Park sections; **Fig. 2.26C**), probably developed as previously deposited gravels failed and slumped downslope. Hence, these irregular pockets of the PRF were likely formed by short-travelled coarse-grained subaqueous gravity flows. The restriction of the PRF to channels cut into the underlying Scarborough Formation along the Bluffs suggests that deposition of the PRF is closely linked with the formation of these channels in a delta top/delta front environment. Well-developed channelized gravels and sands of the PRF are in situ remnants of the shifting channel network, and irregular pockets or crude channels of gravel are well-developed channel facies which slumped in the delta front environment.

2.3.3 BASAL CONTACT OF THE SUNNYBROOK

Description

The nature of the basal contact of the Sunnybrook with the Scarborough or Pottery Road Formations is crucial to interpretations of the Sunnybrook's depositional history. On a regional scale, the contact between Scarborough and Pottery Road Formations and the overlying Sunnybrook is abrupt, with the Sunnybrook draping the channelized top of the Scarborough Formation **(Fig. 2.1a)**. Along the Bluffs at sections on the relative "highs", the elevation of the basal contact varies from 110m (western Bluffs) to 118m (eastern Bluffs; **Table 2.4**) and has a planar geometry **(Fig. 2.27)**. Along the Rouge River Valley, the elevation of the basal contact ranges between 111 and 116m.

	west SCARBOROUGH BLUFFS east								ROUGE R.	
site	9320	9314A	9314	9313	9325	9317	9301	9323	9324	9326
BCE	110m	113m	113m	113m	112m	118m	118m	109m	116m	111m

Table 2.4: Basal contact elevations (BCE) for "high" sections along Scarborough Bluffs presented west to east -- sections 9320 to 9323. Sections 9324 and 9326 are from the Rouge River Valley showing the regional variability of the basal contact elevation. Refer to Figure 2.1 for exact site locations.

Most of the "high" sections along the Bluffs (except 9323) show basal contacts of the Sunnybrook diamict characterized by an interbedded zone of predominantly massive sands and laminated muds (logged as Si(Fm,Sm]) - herein

Figure 2.27: A) Planar upper and lower contacts (arrowed) of the Sunnybrook at the HI section (section 9325; **Fig. 2.1a**). Dark (wet) horizons are clay rich portions of the upper Scarborough Formation. Shovel, located in the centre of the photo along the basal contact, (circled) is 1 m tall. Sunnybrook thickness (distance between the arrows) is approximately 7m. **B)** Lower contact of the Sunnybrook (arrowed) on undisturbed interbedded sands and muds of the Scarborough Formation (Rouge section 9326; **Fig. 2.1b**). **C)** Flat-lying basal contact of the Sunnybrook diamict (arrowed) at Cathedral Bluffs. Section 9313 (**Fig. 2.1a**) is located towards the left hand side of this outcrop. Sunnybrook is 6m thick. **D)** Planar geometry of the top of the Scarborough clay (lower arrow) and the basal and upper contacts of the Sunnybrook (upper arrows) near sections 9314 and 9314A (western Bluffs; **Fig. 2.1a**). Vertical relief of the Bluffs is approximately 45m.

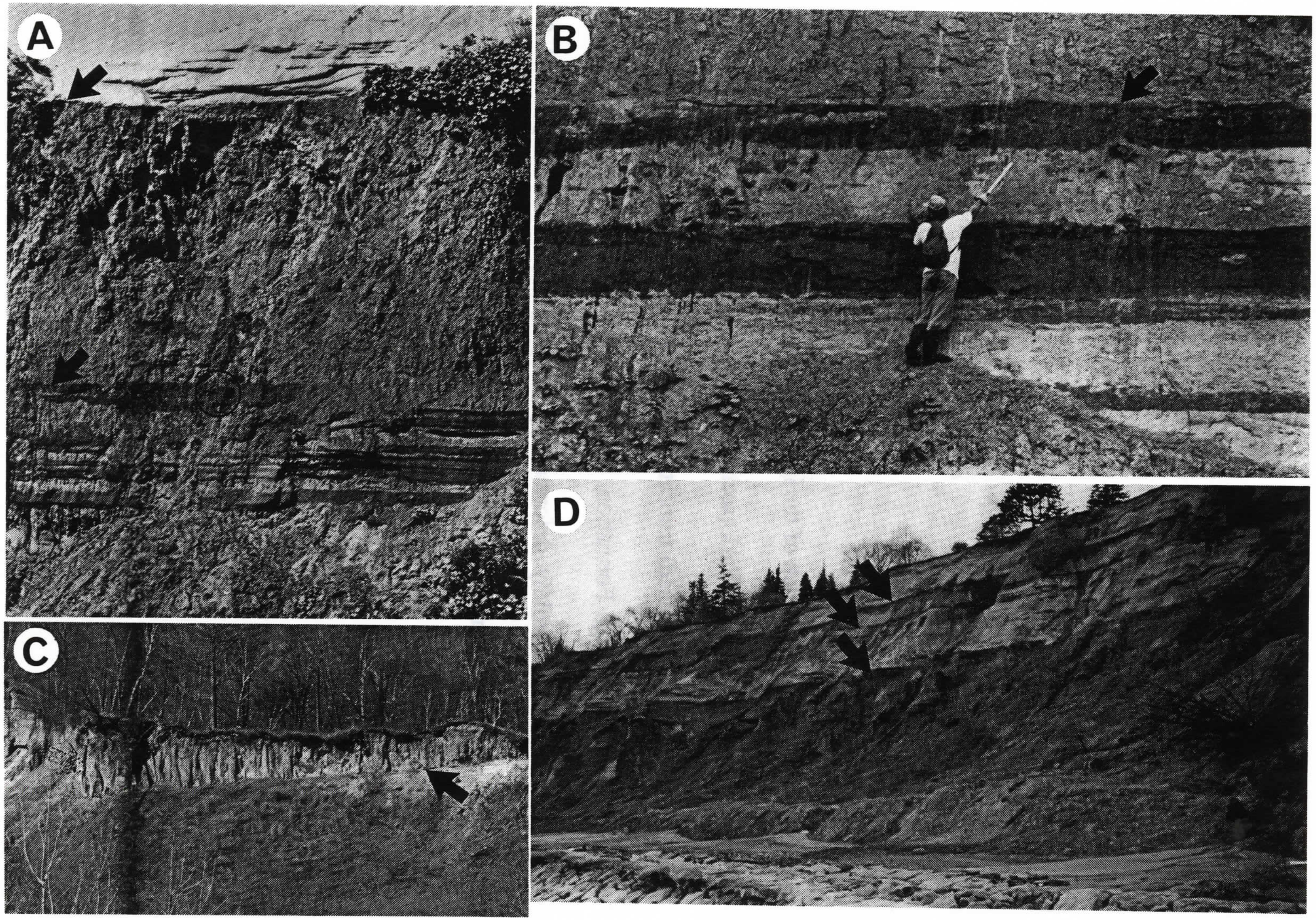
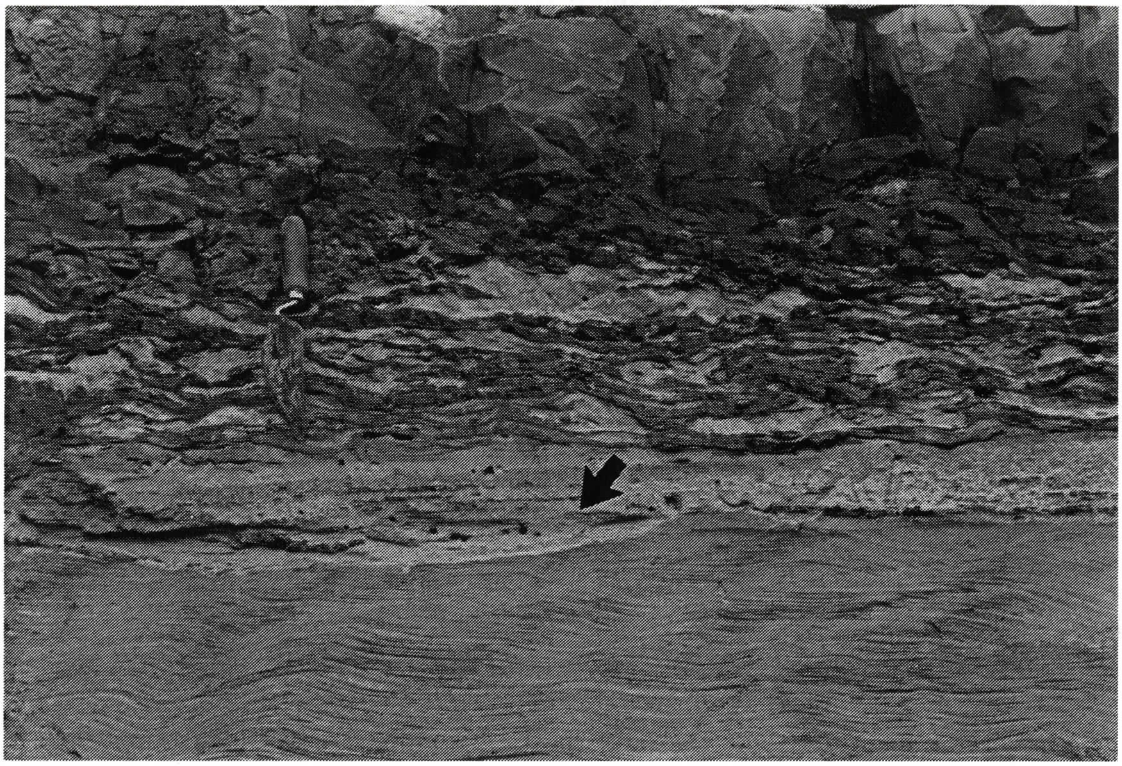
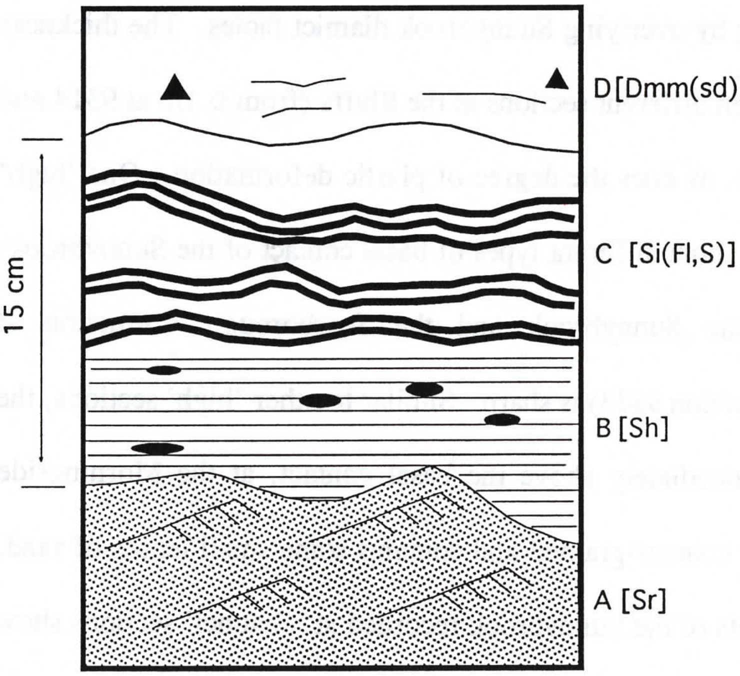

A
B
C
D

Figure 2.28: Photo and sketch of the interbedded Contact Zone (ICZ) at the base of the Sunnybrook at Sylvan Park (section 9301; **Fig. 2.1a**). Horizontally bedded sand with mud chips (arrowed) truncate an undeformed climbing ripple sequence of the upper Scarborough Formation. Interbedded laminated muds and massive sand beds have been mildly deformed by warping due to the deposition of overlying sediments. Trowel is 25cm long.




D[Dmm(sd)]
C [Si(Fl,S)]
15 cm
B [Sh]
A [Sr]

referred to as the Interbedded Contact Zone (ICZ). The base of the ICZ has a slightly scoured contact with the underlying Scarborough Formation; horizontally-bedded sands (Sh), with discontinuous mud horizons and mud clasts, truncate the organic-rich climbing ripple sequence of the underlying Scarborough Formation (units A and B on **Fig. 2.28**). Overlying these Sh sands are a series of finely interbedded massive or rippled sand and laminated mud beds. Thicknesses of the sand and mud beds are variable, but generally do not exceed 2-3cm; the thickness of individual mud laminae is approximately 1mm. Sands from the ICZ (units B and C; **Fig. 2.28**) are better sorted than those of the Scarborough Formation (unit A; **Fig. 2.28**), with significantly less organic material present. Mud beds appear wavy; this distortion was probably caused by limited plastic deformation as a result of vertical loading by overlying Sunnybrook diamict facies. The thickness of the ICZ varies between different sections at the Bluffs (from 0.1m at 9314 and 9314A to 0.5m at 9325), as does the degree of plastic deformation. One 'high' section along the Bluffs show different types of basal contact of the Sunnybrook; the contact between the Sunnybrook and the Scarborough Formation at Morningside Avenue (section 9323) is sharp. Similar to other 'high' sections, the Sunnybrook diamict immediately above the basal contact, at the Morningside Ave. section, is slightly coarser-grained and contains some small lenses of sand.

The basal contacts of the Sunnybrook recorded at 'channel' sections show more variability than those at 'high' sections and may be either conformable or unconformable. Near the 'top' of channels (approximately 10m below the

Scarborough delta top), Bluff channel sections 9315 and 9318 have interbedded contacts (logged Si(Fm,Sm) and Si(F,S)), similar to the described ICZ. Closer to the bottoms of channels (>20m below the Scarborough delta top) and along the channel sides, Bluff channel sections 9303A and 9311 show more abrupt contacts, showing a sharp facies change from Sunnybrook diamict to underlying PRF gravels and Scarborough Formation sands.

Channel contacts are often more complex due to more intensive deformation of the upper Scarborough Formation sediments at 'channel' sections. Extensive deformation of the Scarborough below the basal contact of the Sunnybrook was found at the Guild Inn (section 9311; **Fig. 2.25A**), and probably developed in response to gravity flow processes which were occurring as the channels were formed (see section 2.3.1).

Interpretation:

Examination of the basal contact of the Sunnybrook shows that on the 'high' sections a gradual transition in depositional conditions occurred. The thick rippled, organic-rich sands of the Scarborough Formation were deposited by traction currents, possibly generated by density underflows which carried abundant fine-grained sediment in suspension (**Fig. 2.29**). Changes in flow conditions are then recorded by the ICZ on the highs along the Bluffs. Here, rippled sands were slightly scoured by slightly higher velocity currents which deposited relatively better sorted horizontally-bedded sands with low organic component (unit B; **Figs. 2.28** and **2.29**). Alternating current energies led to the

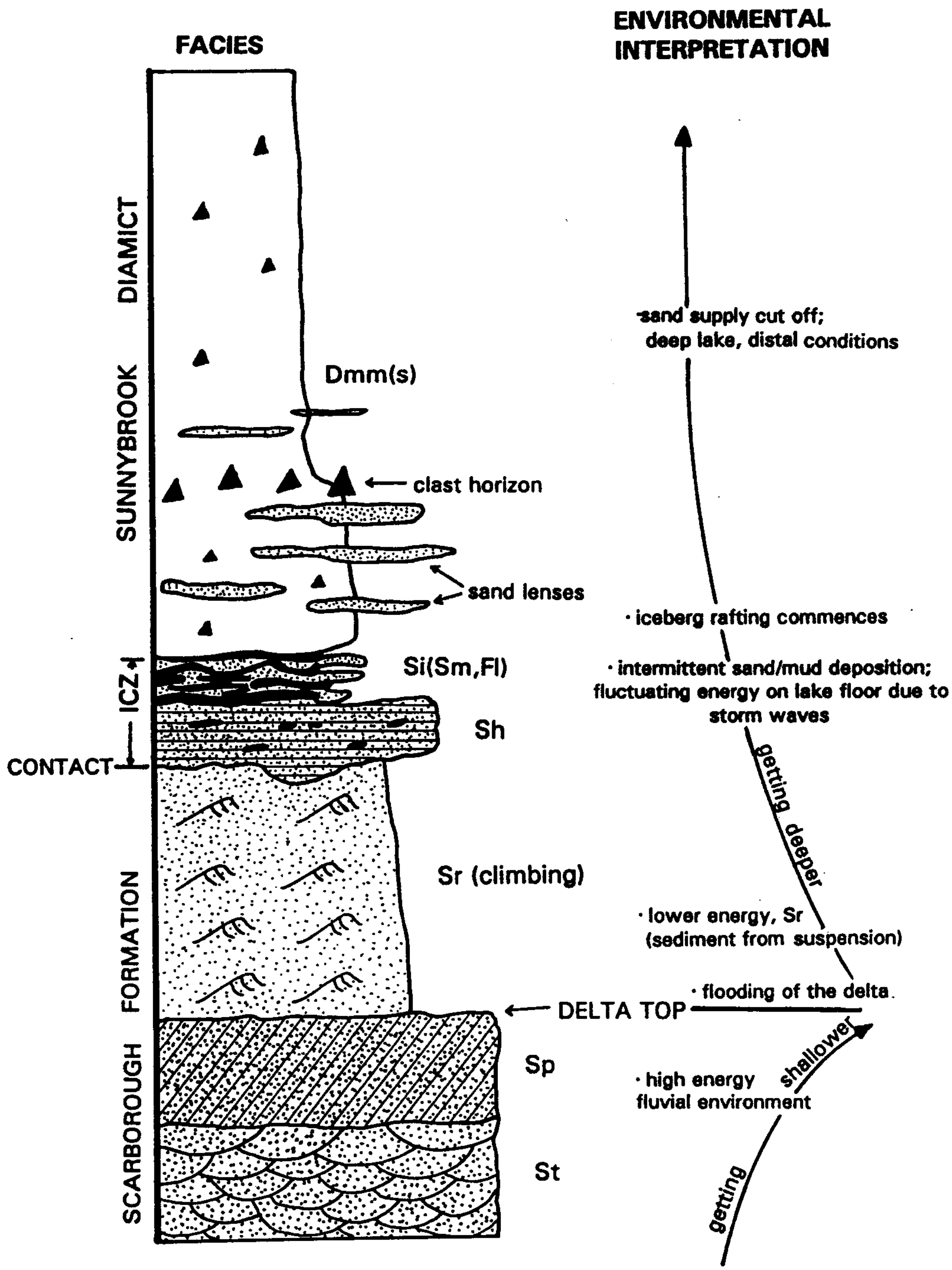


Figure 2.29: Schematic representation of the transition from upper Scarborough facies to those of the lowermost Sunnybrook diamict. Shallowing conditions are represented by the coarsening-upwards sequence within the Scarborough, ending with the St and Sp facies. Flooding of the delta top (Sr facies) is followed by progressively deeper glaciolacustrine conditions.

deposition of the interbedded laminated mud and predominantly massive and rippled sand (unit C on **Fig. 2.28**; Si[Sm,Fl] facies on **Fig. 2.29**). Laminated muds represent periods of 'quiet water' (low energy) deposition in a lacustrine setting; massive and rippled sands represent episodic inflows of higher energy currents, possibly density underflows or storm generated lake bottom currents. Sands beds and lenses become less frequent upsection (**Fig. 2.28**) suggesting that quiet depositional conditions (e.g. lacustrine) prevailed. As well, mud interbeds pass transitionally into diamict which implies the persistance of low energy and possibly deeper water conditions through deposition of the lowermost diamict; diamict facies accumulated primarily through 'rain-out' (see section 2.1). In the lowermost diamict facies, sand lenses represent infrequent currents which locally re-distributed lake bottom sandy sediments. On the highs, the ICZ is therefore a transitional contact zone, with little or no break in the depositional sequence from relatively shallow water Scarborough Formation to deeper water Sunnybrook Drift (**Fig. 2.29**).

Channel areas, already subaqueous at the time of flooding of the Scarborough delta top, have contacts which **do not** consistently represent deepening water conditions at the beginning of the Sunnybrook interval. Only at two "shallower" sections (9315 and 9318), approximately 10m below the delta top, is the basal contact of the Sunnybrook interbedded. At these sites, the contact represents a progressive change in depositional conditions similar to that discussed for the ICZ formation on the relative highs (see above). In these relatively 'high' positions in the channels, water depths were shallow enough to allow sands to be deposited by intermittent traction currents. At sites lower within the channels (sections 9303A, 9303B; **Fig. 2.21A**) the change from sand to diamict deposition was abrupt.

The nature of contacts between the Sunnybrook and underlying formations raises questions as to when channels cut into the Scarborough Formation formed. Abrupt contacts in channel areas suggest that the channels formed before the deposition of the Pottery Road Formation and Sunnybrook sediments, and may represent a short hiatus. However, transitional contacts between the Scarborough Formation and the Sunnybrook on the highs clearly represent a gradual change from deltaic Scarborough and to deep-water glaciolacustrine Sunnybrook conditions and **do not** suggest an hiatus between Scarborough/PRF and Sunnybrook environments. The formation of these channels cut into the Scarborough and their implications to the Sunnybrook depositional environment will be discussed in more detail in chapter 5.

2.3.4 UPPER CONTACTS OF THE SUNNYBROOK

The Sunnybrook is either conformably overlain by sediments of the Thorncliffe Formation or unconformably overlain by Late Wisconsin Halton Till or post-glacial Lake Iroquois deposits (**Fig. 2.1**).

2.3.4a Upper Contacts with Lower Thorncliffe Formation

This study is concerned only with Thorncliffe sediments in immediate contact with the Sunnybrook (i.e. within one metre of the Sunnybrook's upper contact). Thorncliffe sediments logged in this study, contain a variety of facies types and structures, dominated by deformed sand but also including massive sand, massive mud, and laminated and cross-bedded sands. Mechanical sieving of Thorncliffe samples yielded a distinctive silty sand texture (Appendix B).

In the central Bluffs area (sections 9313, 9325, 9317, 9302, 9301; **Fig. 2.1a**) and the Rouge River Valley (sections 9308, 9307, 9306, 9305, 9304, 9324; **Fig. 2.1b**), the upper contact of the Sunnybrook with the overlying Thorncliffe Formation is regionally flat (elevation along the Bluffs of 119-125 m.a.s.l.; elevation in the Rouge Valley of 121-127 m.a.s.l.; **Fig. 2.1**), but has considerable local relief. Local relief is due to reverse density loading of sandy balls and pillows of the Lower Thorncliffe formation into the underlying Sunnybrook diamict (**Figs. 2.1**, **2.5**, and **2.31C**). The largest of these sand pillows has dimensions of 2m deep x 8m wide (**Figs. 2.30** and **2.31A**); Eyles (1982) measured some equally large pillows in the central area of the Bluffs. The pillows contain a chaotic mix of deformed sand facies (Sd facies: **Fig. 2.30**), and rarely display any original bedding. Detached sand balls (of the Thorncliffe Formation) are "ingested" by diapirs of diamict along the top of the Sunnybrook diamict (**Fig. 2.31B**).

In the central Bluffs area (sections indicated above), contacts between the Sunnybrook diamict and the overlying Lower Thorncliffe are interpreted as conformable. In these areas, reverse density gradients and high sediment pore

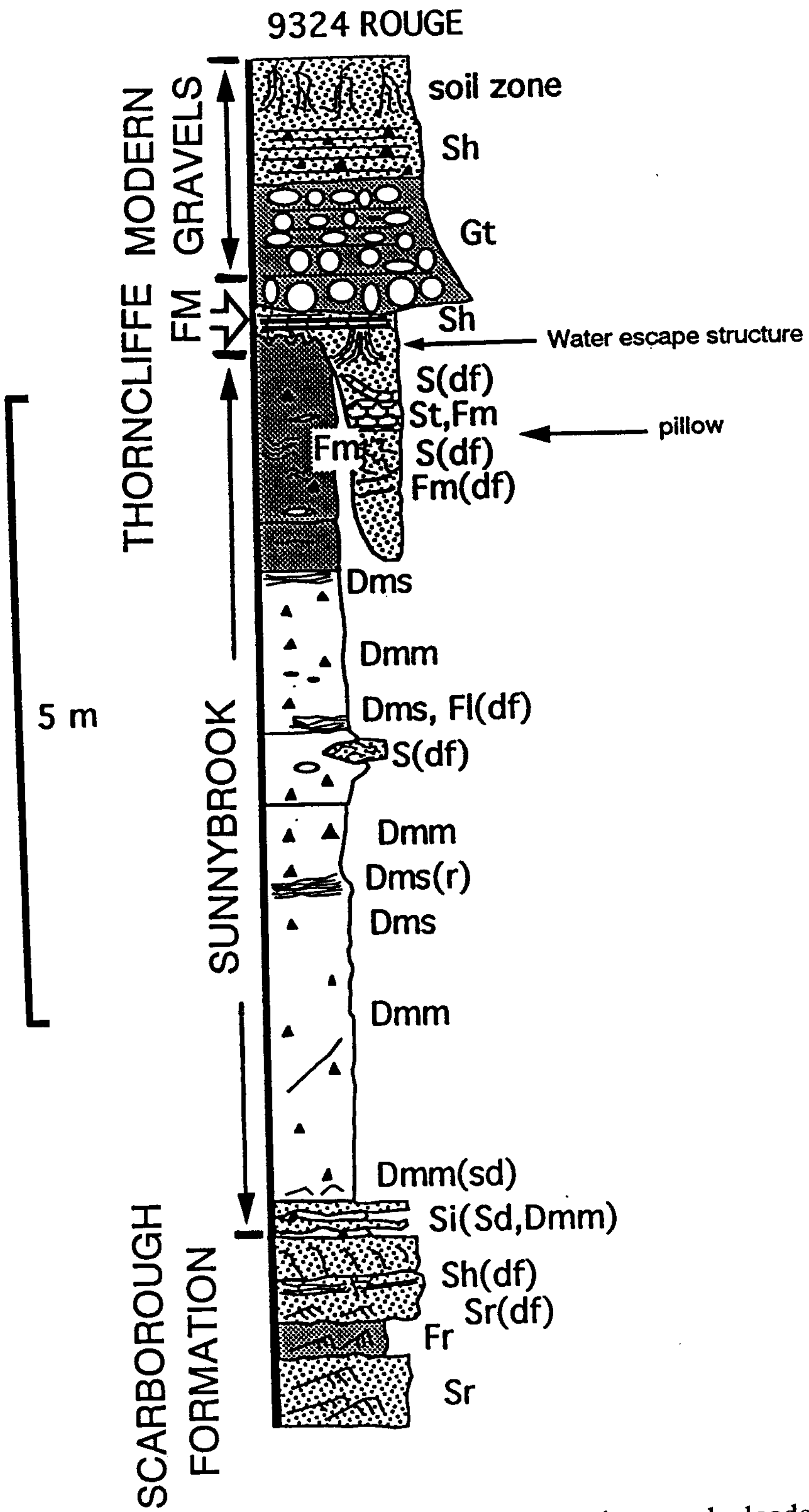
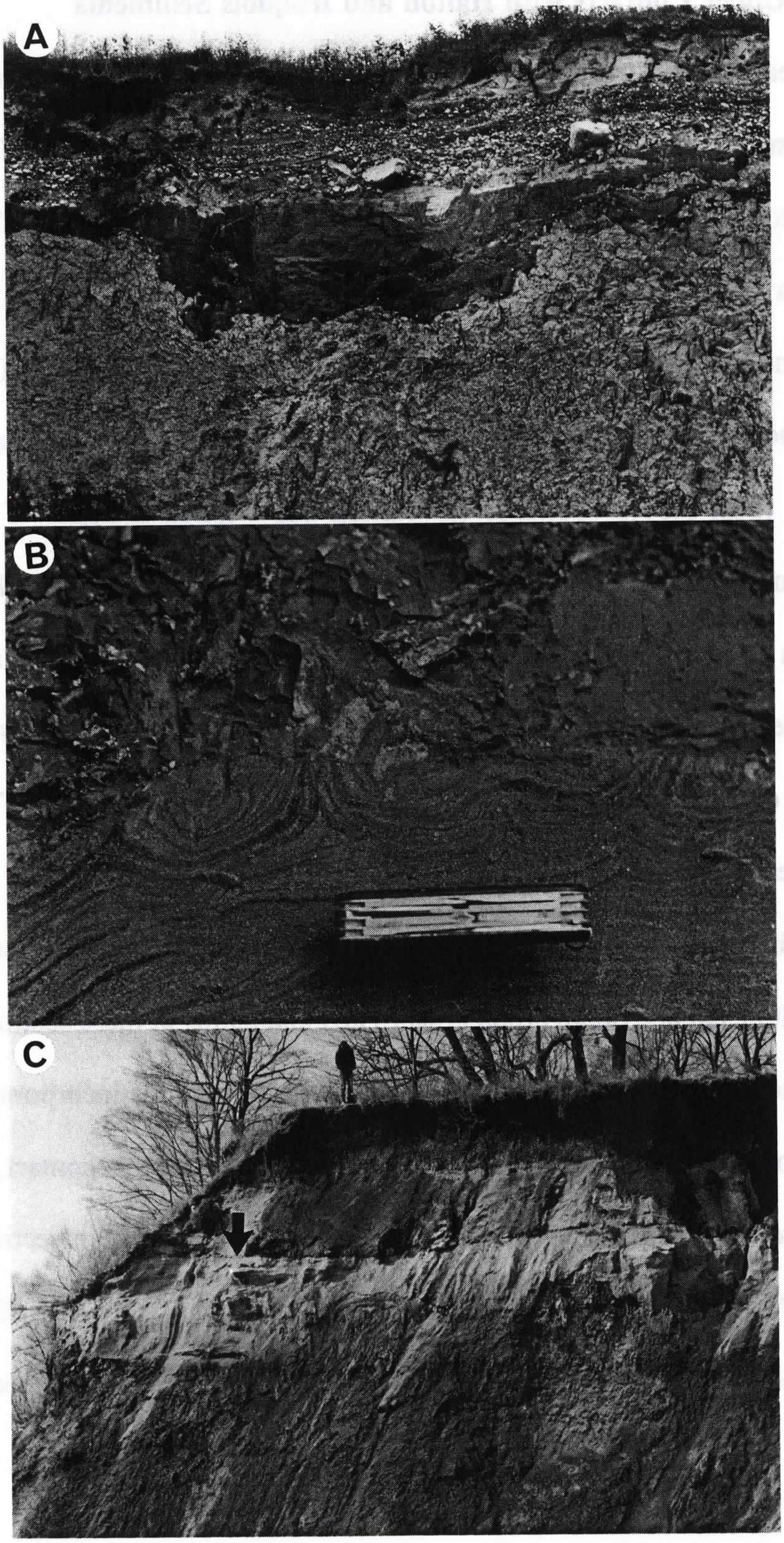


Figure 2.30: Large pillow of Thorncliffe Formation sands loaded into fine-grained clast-poor Sunnybrook at section 9324 in the Rouge Valley. Pillow shows extensive deformation of sediment due to reverse density loading: a water escape structure is visible at top of the pillow.

water pressures, set up by rapid emplacement of dense sands above a partially saturated muddy substrate, are thought to have triggered much of the deformation preserved at this contact (Clark, 1986).

In the "channel" areas along the Bluffs (e.g. Dutch Church, **Fig. 2.13**), the contact between laminated Sunnybrook and Lower Thorncliffe Formation is gradational. The exact location of the contact between the two formations is difficult to determine due to progressive facies changes. Laminated Sunnybrook facies become progressively more sandy upsection, passing from predominantly D-division turbidites with only thin sand horizons (<3mm at the base) to thicker turbidite beds with thicker sand horizons (C-division, Bouma sequence) towards the top (**Fig. 2.17**). A similar increasing trend in sand bed thickness at the Dutch Church section was described by Clark (1986). In the present study, the contact between laminated Sunnybrook and Thorncliffe Formation is identified as the point when the predominant matrix material becomes sand (logged as Sm(sd), S(df): see 9303A log: **Fig. 2.1a** and **Fig. 2.13**). Others (Eyles and Clark, 1988b) have suggested the contact be drawn when the ice rafted component, within the laminated facies, disappears.

Figure 2.31 Upper contact of Sunnybrook diamict: **A)** Large pillow of Lower Thorncliffe sand (dark coloured) loaded into fine-grained clast poor Sunnybrook (facies Fm) at section 9324 (Rouge; **Fig. 2.1b**). Dimensions of the pillow are 8m wide x 2m deep; it is unconformably overlain by Holocene fluvial gravels. **B)** Upper contact of a loaded sand ball within upper Sunnybrook diamict (Rouge section 9304; **Fig. 2.1b**). There is a sharp contact between de-watered sands and diamict diapir above. Knife handle is 9 cm long. **C)** Undulating geometry of the upper contact of the Sunnybrook at Sylvan Park (section 9302; **Fig. 2.1a**). Pillows of Lower Thorncliffe sands (light-coloured unit) load into massive fine-grained diamict facies. The vertical relief of the contact is approximately 1.5-2m. The Thorncliffe formation is truncated by the boulder lag (arrowed) of the overlying Lake Iroquois deposits.


A
B
C

2.3.4b Upper Contacts with Halton and Iroquois Sediments

At the eastern and western extremities of the Scarborough Bluffs and in the creek exposures, the Sunnybrook is erosionally truncated by either the Late Wisconsin Halton Till or postglacial Lake Iroquois deposits. The Halton Till is interpreted as a "deformation till" deposited by late Wisconsin ice (Boyce and Eyles, 1991) and shows evidence of incorporation of underlying sediments (i.e. those of Thorncliffe and Sunnybrook) as they were overridden, producing a chaotic deposit (**Fig. 2.32**). Towards the eastern and western margins of the Bluffs, the Sunnybrook and Thorncliffe formations were completely removed by Late Wisconsin erosion (sections 9322, 9321, 9316 and 9312; **Figs. 2.1a** and **2.32**). Here, the Halton Till rests directly upon Scarborough Formation deposits.

In creek exposures (sections 9326, 9309, 9307; **Fig. 2.1b**), the Halton Till directly overlies the Sunnybrook and displaced rafts of Sunnybrook are identifiable within the Halton Till in sections 9326 and 9307. The contact between the Halton Till and Sunnybrook is sharp and undulating at these sections, with rafts of Thorncliffe, Sunnybrook and Scarborough formations incorporated into lower Halton Till facies (log 9316; **Fig. 2.32**). The relief of this contact, as seen in exposures along the Rouge River, is in excess of 4 m between sections 9307A and 9307B (**Figs. 2.1a** and **2.32**). In walking downstream of section 9308 along the Rouge River, the observed relief of the Halton's basal contact exceeded 10-20 metres.

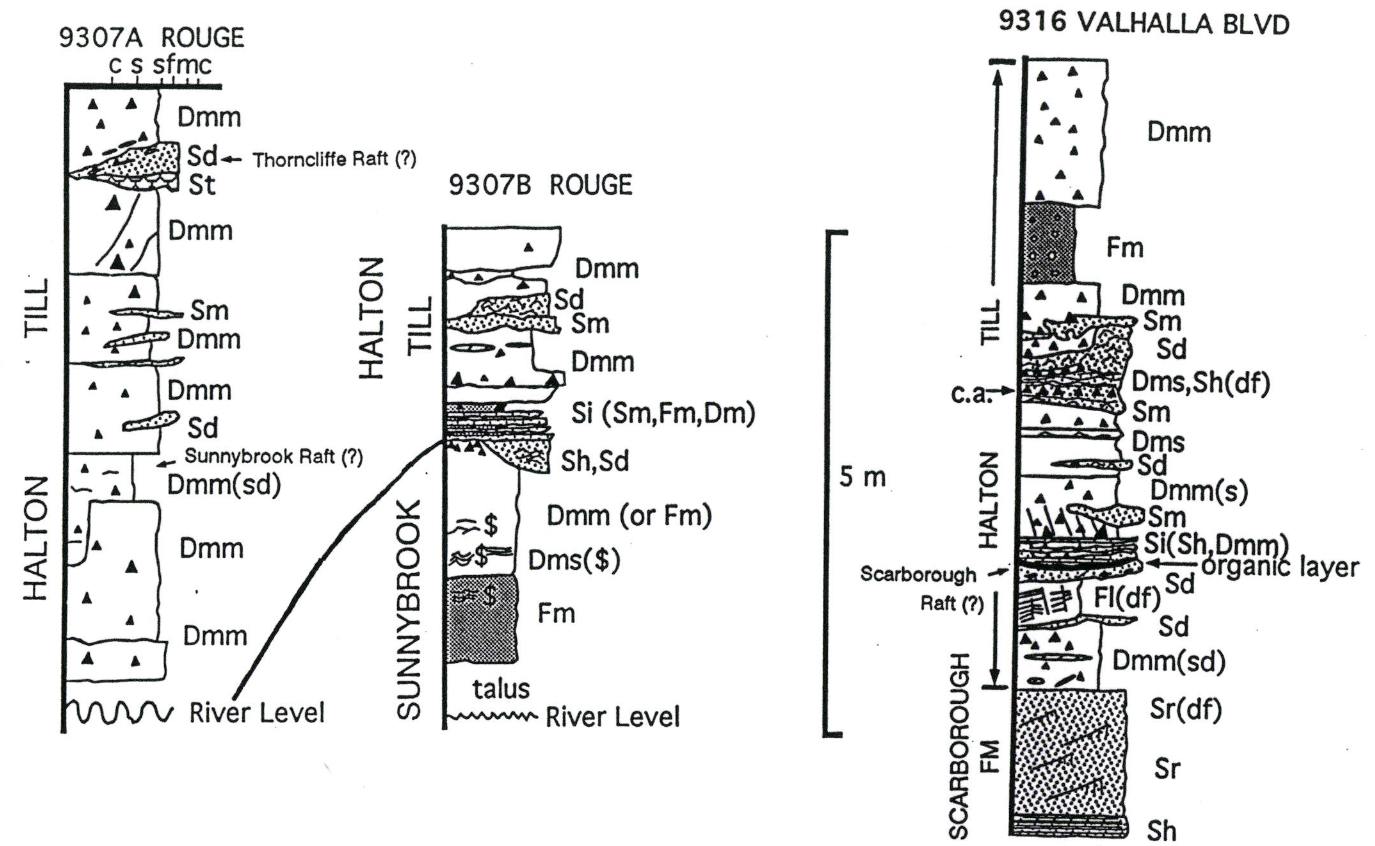


Figure 2.32: Halton "deformation till" facies in Rouge and Scarborough Bluff outcrop. The Rouge Valley logs (9307A,B; **Fig. 2.1b**) show a downstream change in the elevation of the Halton's basal contact (the two logs are <150m apart) -- the contact is dipping at 14° directly due north. Towards the top of 9307A log, there is a large lenticular raft of Thorncliffe sand; lower log shows some finer-grained diamict which may be rafted Sunnybrook. Log 9316 from the western Bluffs (**Fig. 2.1a**) shows basal incorporation of Scarborough Formation sediments (the distinctive organic-rich layer) into Halton Till facies and an absence of any identifiable Sunnybrook or Thorncliffe formation deposits. Clast accumulation ("c.a.") layers within the Halton Till facies have been documented by J.Boyce (pers. comm., Oct. 1993).

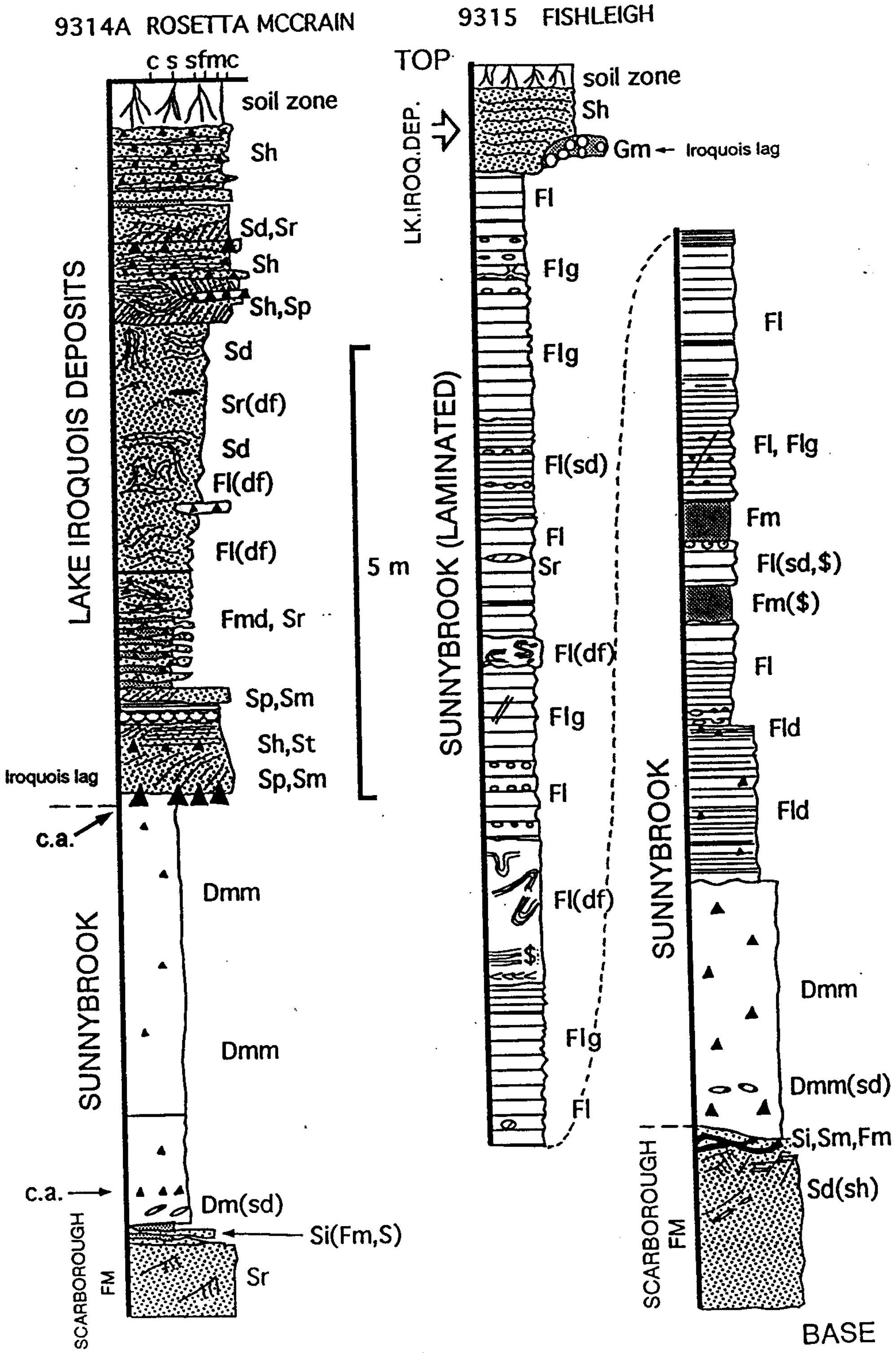


Figure 2.33: Erosional contact of Lake Iroquois deposits with the underlying Sunnybrook. A clast lag (upper c.a. in 9314A, Gm bed in 9315) marks this contact.

Postglacial shoreline erosion, during Lake Iroquois time (approximately 11,500 years B.P.), removed a great deal of the original stratigraphic sequence exposed at the Scarborough Bluffs. Deposits attributed to glacial Lake Iroquois truncate the Sunnybrook diamict at sections west of Fishleigh Drive (section 9315; **Fig. 2.1a**), and have affected overlying formations (e.g. Lower Thorncliffe at Sylvan Park; **Fig. 2.1a**). Sediments deposited by Lake Iroquois show erosional contacts with underlying sediments, and are identified by their characteristic clast lags and shoreline facies (**Fig. 2.33**).

2.4 CONCLUSION

This chapter provides a summary of facies characteristics identified during fieldwork and an initial environmental interpretation of each of the facies types. Descriptions of the Sunnybrook and relevant portions of Scarborough, Pottery Road, and Lower Thorncliffe Formations best support a subaqueous interpretation for the Sunnybrook. A glaciolacustrine origin is suggested for the Sunnybrook on the basis of the following characteristics. Firstly, the presence of continuous, unbroken laminated clay beds **within** massive diamict facies documents quiet rain-out of muds during diamict accumulation. Secondly, horizons of silt clast breccia within massive diamict facies were formed during resedimentation of fine-grained lake floor sediments by subaqeuous slumping. Thirdly, the interbedded contact zone (ICZ) records a gradual transition from shallow to deep lacustrine conditions at the beginning of the Sunnybrook interval. Fourthly, the Sunnybrook diamict facies show a close association to under- and overlying lacustrine deposits. For example, the Sunnybrook's laminated facies, which overlie the Sunnybrook diamict, contain rafts and re-sedimented diamict clasts, and were deposited by a series of turbidity currents focused into subaqueous channels. Finally, the glaciolacustrine interpretation proposed for deposition of the Sunnybrook is strengthened by the absence of any indicators (such as erosional basal contacts, basal contacts showing marked relief, or incorporation of underlying sediments) which might suggest a subglacial origin.

CHAPTER 3:
FACIES ASSOCIATIONS and DEPOSITIONAL MODEL

3.0 INTRODUCTION

Facies are the product of individual depositional processes which may operate in a number of different environments. Interpretations of depositional environment for ancient sediments require a description of 'facies associations', which are the product of groups or combinations of these processes. Given the facies types discussed in chapter 2, two facies associations are proposed for the Sunnybrook based on common facies groupings and geometries for exposures along the Scarborough Bluffs. These are: 1) 'Channel' Facies Association, and 2) 'High' Facies Association (**Fig. 3.1**).

The pre-Sunnybrook topography plays an important role in the distribution of Sunnybrook facies types and is instrumental in defining the two facies associations. The Channel Facies Association (CFA) is defined for Bluff exposures where discrete topographic lows or 'channels' on the upper surface of the Scarborough Formation are clearly recognized. The axes of these channels at the Bluffs are oriented nearly orthogonal to the modern Lake Ontario shoreline; thus exposed sediments infilling these channels show transverse cross-section. For outcrop in the dissecting creeks, in the absence of extensive exposure of basal contacts, associations are identified solely by comparison to the defined Bluff

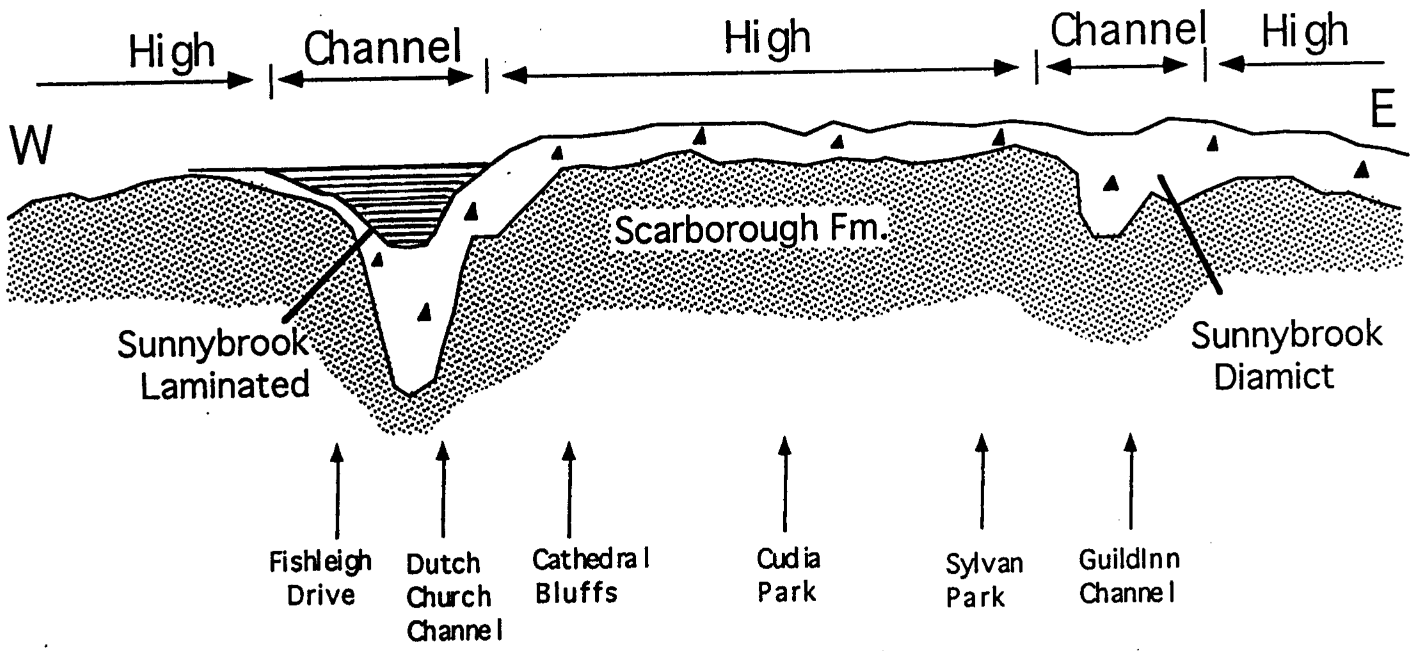


Figure 3.1: Location of channels and relative highs along the Scarborough Bluffs. A thickened diamict drape (in channels), infilled with laminated sediments, characterizes the Channel Facies Association (CFA). A thinner drape of massive diamict with an interbedded basal contact zone and basal clast horizons (on relative highs) characterize the High Facies Association (HFA) -- see text.

facies associations.

The Channel Facies Association (CFA) comprises a thick unit of predominantly massive diamict (10 to 18m thick) conformably overlain by a succession of finely and thickly bedded turbidites (**Figs. 2.1a** and **3.1**) -- individual turbidite beds have thicknesses ranging from less than 0.5 cm to approximately 100 cm. Along the Bluffs, the CFA is present within large channels cut into the top of the Scarborough Formation (**Fig. 2.1a**); Clark (1986) described a similar facies association in a 10m-thick channel fill of laminated Sunnybrook outcropping in Duffins Creek where topographic lows are formed by a pre-existing bedrock channel network (**Fig. 3.2**; Eyles, N. et al., 1985). This network of bedrock channels is associated with a regional Tertiary drainage pattern (described by Spencer, 1890) in which lakes Huron and Ontario were linked by the Laurentian River.

The High Facies Association (HFA) of the Sunnybrook consists of a 5 to 7 m thick drape of massive and stratified diamict facies, and has distinctive sedimentological characteristics including basal clast horizons and an interbedded basal contact zone. The HFA of the Sunnybrook is located away from topographic lows in the substrate, forming planar tabular depositional units on relative highs (**Fig. 3.1**).

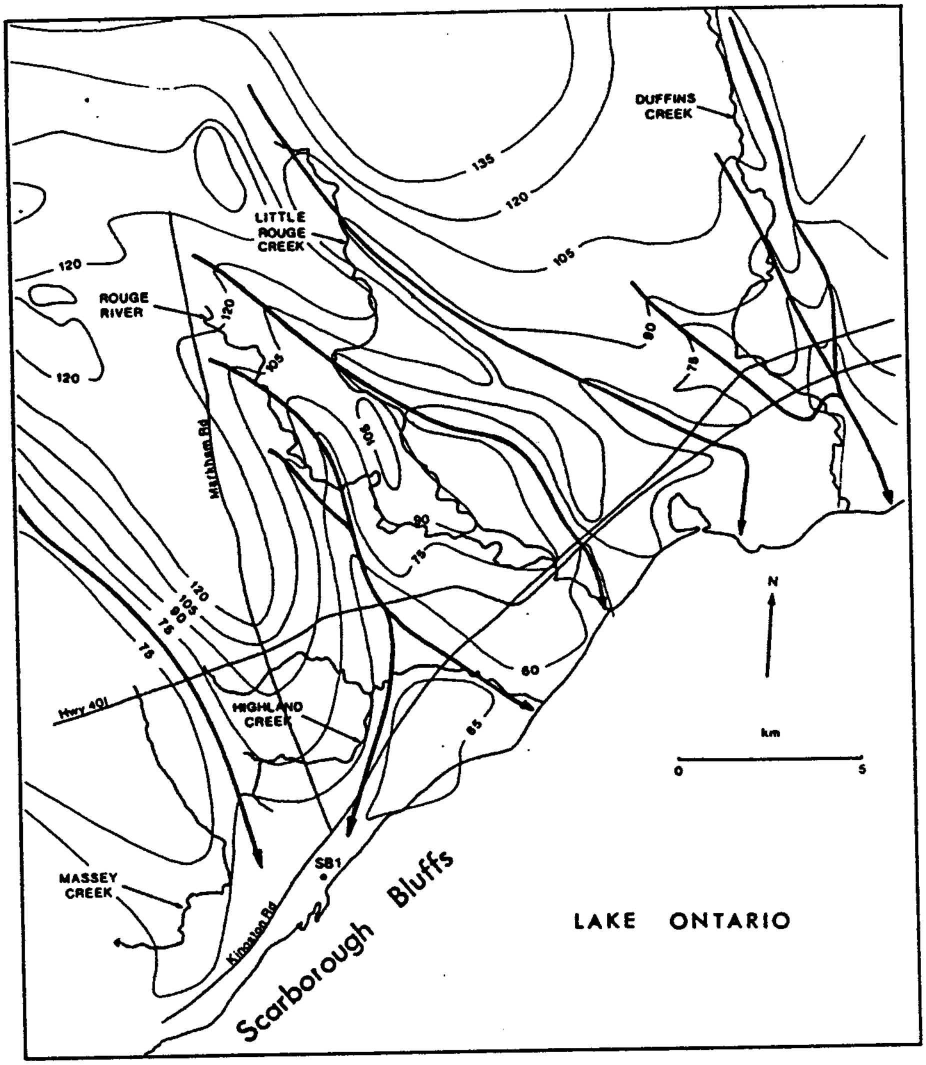


Figure 3.2: Bedrock contour map showing a complex channel system which probably formed part of the pre-glacial Laurentian Channel system (Spencer, 1890). Bedrock channels are designated by arrows and the contour interval is 15m. Note that the present Highland Creek, Rouge River, and Duffins Creek Valleys occupy the approximate position of the bedrock channels. The Scarborough formation's deltaic sands were deposited in the vicinity of SB1 and in Highland and Rouge Valleys by a large river occupying the deepest channel (i.e. the channel flanked by the 75m contours on the left side of the figure). The Sunnybrook drapes over the underlying channelized Scarborough formation or bedrock, and sits within the bedrock channel in the Duffins Creek Valley. Source: Eyles, N. et al., 1985.

3.1 CHANNEL FACIES ASSOCIATION (CFA)

3.1.1 GENERAL

The CFA infills large channels cut into the underlying Scarborough Formation along the Scarborough Bluffs and fills bedrock channels in the Duffins Creek area. Three channels cut into the Scarborough Formation were identified by Karrow (1967) along the Bluffs at Dutch Church, Guild Inn and Beechgrove Drive (**Fig. 1.2**). However, in this study, the CFA is only identified in the Dutch Church and Guild Inn channels (**Fig. 3.1**); at the Beechgrove channel, the Sunnybrook is absent, and was presumably re-worked into the Halton Till facies which form the channel fill here (**Fig. 1.2**). These channels have variable depths (from 16 to 53m) and widths (from 1.5 to 1.75km), and channel margin slopes range from 1° to 4°.

The elevations of Sunnybrook lower and upper contacts were measured (**Table 3.1**). For the CFA, the elevation of the lower contact is highly variable and ranges from 106 to <75m a.s.l., depending on the depth of the infilled channel; note that the basal contact in the Dutch Church channel is below the level of modern Lake Ontario. An in situ upper contact (with elevation 122m) for the CFA exists only at the Dutch Church section, and has an equivalent elevation to the upper contact of the HFA. At other sections, the uppermost facies of the CFA have been removed by either the late Wisconsin ice advance (Halton Till) or erosional processes associated with postglacial Lake Iroquois.

LOWER CONTACT			UPPER CONTACT		
CFA	**HFA**	**Rouge**	**CFA**	**HFA**	**Rouge**
99	110	116	122	119	127
89	113	112		119	126
105	113			124	127
106	113			125	121
	112				125
	118				123
	118				
	109				
<75-106	**113(8)**	**114(2)**	**122(1)**	**122(4)**	**125(6)**

Table 3.1: Sunnybrook upper and lower contact elevations for both channel and high facies associations (CFA and HFA) along the Bluffs and for sections in the Rouge Valley. All measurements are in metres above sea level; lowest row of data (**bolded**) are averages, with the number of averaged data points in parentheses. No average value is given for the basal contact of the CFA as these vary greatly; the basal contact of the Sunnybrook in the Dutch Church channel is below modern lake level (i.e. <75m.a.s.l.; **Fig. 2.1a**).

3.1.2 FACIES OF THE CFA

At the Dutch Church section, the CFA is characterized by a thick package (10-18m) of massive and stratified diamicts (Dmm and Dms facies) containing flow noses and silt clast breccia horizons which give evidence of resedimentation processes. The diamict drape thins away from the channel axis, toward the margins where it is commonly less than 3m thick (Bluffers Park and Fishleigh sections: 9303B and 9315; **Fig. 2.1a; Table 3.2**). The diamict drape is thickest in channel bottoms where sediment is focused into lows by resedimentation processes. The variable thickness of diamict within the Sunnybrook (approximately 10 to 18m in channels; 5 to 7m on highs; **Table 3.2**) can be used to qualitatively infer the relative importance of slumping. The thicker the

site	high or channel	diamict facies thickness	laminated facies thickness
9322	h	0	0
9321	h	0	0
9316	h	0	0
9312	h	0	0
9320	h	1.7*	0
9314	h	4.0*	0
9314A	h	4.6*	0
9315	**ch**	**2.7**	**18.0***
9303A	**ch**	**10.1**	**25.4**
9303B	**ch**	**2.5**	**10.7**
9313	h	5.7	0.7
9325	h	7.0	<0.1
9317	h	5.4	0.5
9301	h	7.2	<0.1
9318	**ch**	**17.9**	**1.5***
9311	**ch**	**16.5**	**1.1***
9323	h	2.1*	0

Table 3.2: Sunnybrook facies thicknesses (in metres) for Channel and High Facies Associations along the Bluffs. Channel sections - Dutch Church (9303, 9315) and Guild Inn (9318, 9311) - are **bolded**. Asterisks (*) indicate sections where the Sunnybrook has an eroded upper contact; some of the original sediments have been removed by post-Sunnybrook events. Sections are listed west to east along the Bluffs (9322 - west; 9323 - east); for section locations see **figure 2.1**.

diamict drape in channels, relative to accumulated rain-out on the highs, the greater the inferred resedimentation activity. For example, in the Guild Inn channel (sections 9318 and 9311), where thick units of diamict are present (**Table 3.2**), slumping activity is inferred to have been prolific in filling most of the 20 m deep channel.

Grain size analyses of the Sunnybrook diamict matrix presented by Karrow (1967) and Eyles (1982) were subdivided into categories based on facies type and topographic setting (**Table 3.3**), in the hope of establishing granulometric criteria for the discrimination of Channel and High Facies Associations. The analyses of

	Karrow 1967	Eyles 1982 (Dmm)	Eyles 1982 (Dms)
CFA	n=4	n=2	n=4
sand	21	8	11
silt	47	31	33
clay	32	61	56
HFA	n=11	n=4	n=3
sand	17	32	21
silt	33	53	35
clay	50	15	44

Table 3.3: Grain size variation of the Sunnybrook diamict matrix for channel and high facies associations (number of samples processed indicated by 'n'). Massive and stratified diamict facies were sampled by Eyles (1982); Karrow's study (1967) preceded sedimentological discrimination of Sunnybrook facies.

Karrow (1967) suggest that diamicts of the CFA are coarser grained than diamicts of the HFA (**Table 3.3**), with higher sand content in channels, while those of Eyles (1982) document coarser grained diamicts on the highs. Coarser-grained diamicts in channels (Karrow, 1967) suggest that subaqueous slumps may have focused coarser-grained sediments during deposition of the diamict. In modern glaciomarine environments of Alaska and British Columbia, slumping of sediment on glacier-fed deltas deposits coarser-grained sediments along submarine channels and fines on the "interchannel" areas (i.e. highs) (Carlson et al., 1992; Kostachuk et al., 1992; Phillips and Smith, 1992) which may be analogous to conditions at Scarborough during deposition of the Sunnybrook. However, the data of Eyles (1982) show the extreme spatial and vertical textural variability of the diamict and argue against using grain size as diagnostic criteria for environmental reconstruction.

Thus, it is not possible to distinguish between HFA and CFA on the basis of textural variability of the diamict matrix. The Sunnybrook diamict matrix shows a mild fining upwards trend at the Sylvan Park section (**Fig. 2.4**) and may be used to infer deepening lake conditions during the Sunnybrook interval. However, analysis of matrix texture at other sections by Karrow (1967), Eyles, C.H. (1982), and this study is insufficient to demonstrate whether or not this trend exists across the study area. Data are currently inadequate due to small sample numbers and limited sampling in the vertical dimension. Hence, to document textural variation (e.g. both vertical and spatial) of the two facies associations, more comprehensive grain size sampling would be required than was completed by the present study.

Diamicts of the CFA show an abrupt contact with overlying fine-grained laminated facies, which consist predominantly of silt and clay turbidites (Fl, Fld facies: **Fig. 2.13**). The abrupt contact is defined by the sedimentological change from massive to laminated facies types and, in places, by a step-like textural change (e.g. arrowed contact on section 9315; **Fig. 3.3**). Average texture changes from sandy-silt for the diamict matrix to silty-clay for laminated facies; in other sections, textural change is less pronounced (Dutch Church and Bluffers Park sections; **Fig. 3.3**).

Units of undisturbed laminated facies (Fl, Fld facies), with common diamict clasts and horizons of silt clast breccia in the lowest 2-5m of the Sunnybrook CFA, vary in thickness from 11 to 25m (**Table 3.2**) and are interpreted as packages of turbidites. The inclusion of ice-rafted materials (e.g. clasts and diamict clasts) suggest continuation of ice-rafting activity within the lowermost laminated facies (**Fig. 3.3**). The loss of ice-rafted debris upsection indicates that the influence of icebergs and/or floating ice shelves diminished over time, although the lake was probably still dammed by ice at its outlet to the east (see section 3.5).

In the lowermost ice-influenced laminated facies (Fl, Fld; **Fig. 3.4A**) at Dutch Church, a 1m thick unit of massive and stratified diamict facies (Dmm, Dms) occurs. The diamict unit was traced approximately 400m along the Bluffs between Dutch Church and Bluffers Park sections (9303A and 9303B), and eventually pinched out as a lobate form to the west of 9303A (**Fig. 3.3**). The contact between the diamict and over- and underlying laminated facies is undulating and sharp. Laminated facies immediately below the contact may be

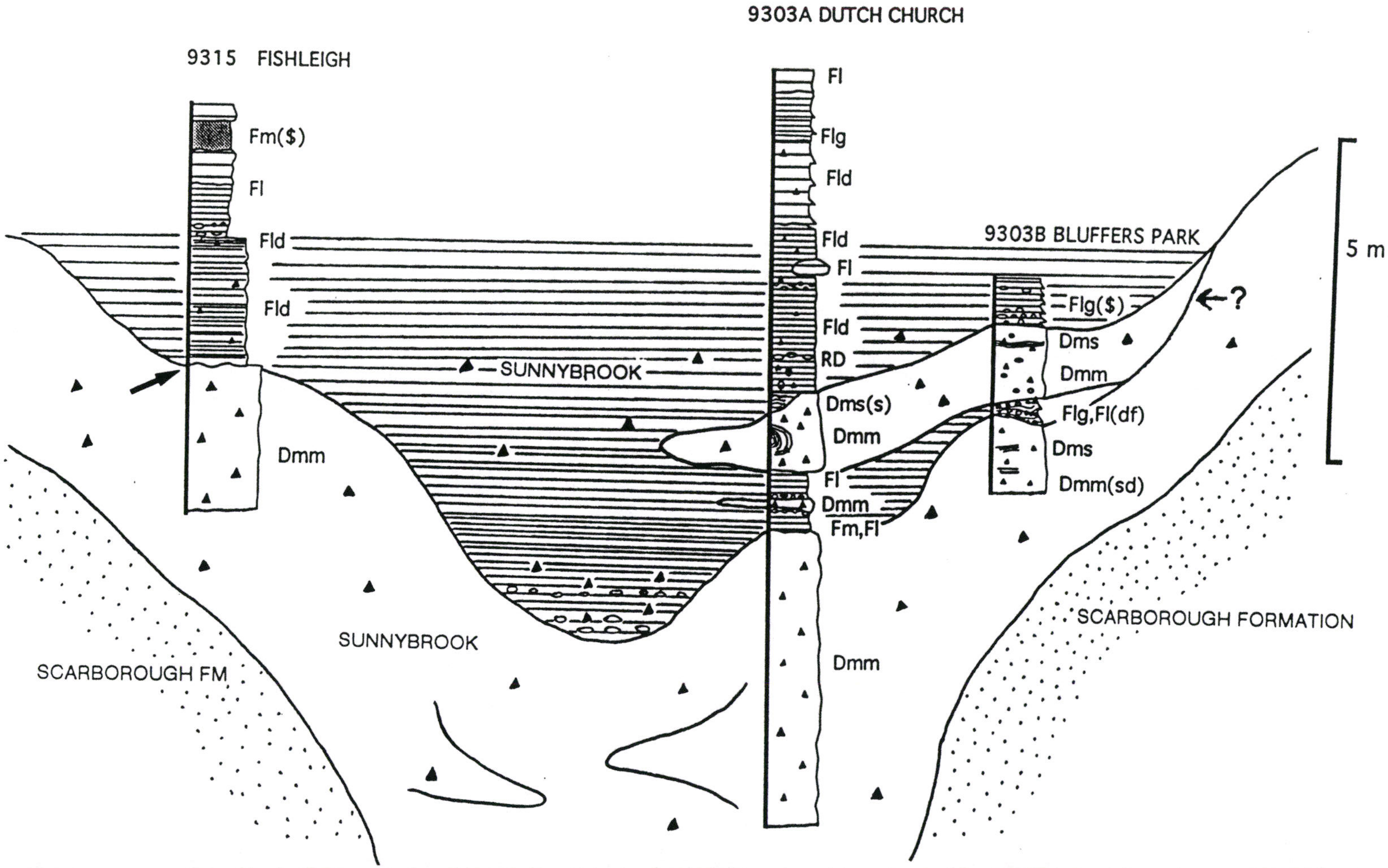
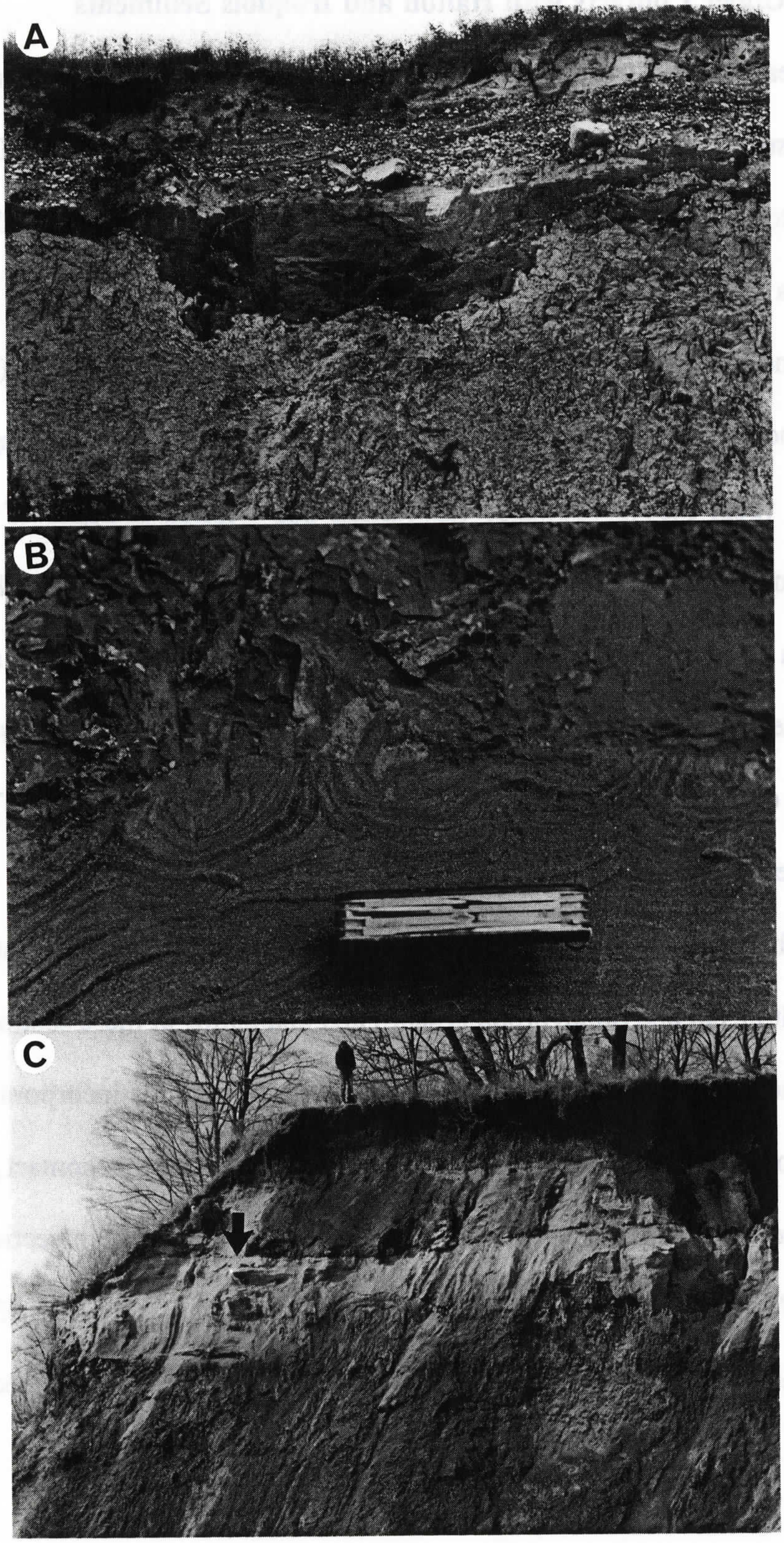


Figure 3.3: Sedimentological character of the CFA in the Dutch Church channel along the Bluffs (see **Fig. 3.1**). Massive diamict facies are conformably overlain by a package of laminated silt and clay turbidites. Lowermost turbidites contain diamict clots, silt clast breccia horizons and dropstones, and are interbedded with large debris flows (entering from the right side in this figure). The contact between diamict and laminated facies is sharp and in places, the diamict is loaded into the underlying laminated facies causing their deformation.

Figure 3.4: A) Undulating contact (lower arrow) between laminated and massive diamict facies of the Sunnybrook at Bluffers Park (section 9303B; **Fig. 3.3**). Diamict facies (upper arrow) are interpreted as a large subaqueous debris flow that has disrupted the underlying laminations. This large flow is not present in logged sections west of the Dutch Church (section 9303A; **Fig. 3.3**). **B)** Base of the "debris flow" bed at Dutch Church (section 9303A; **Fig. 3.3**) shows the incorporation of a graded bed of silt and clay into massive diamict facies. Knife handle is 9 cm long.


A
B
C

deformed by loading (**Fig. 3.4A**) and/or incorporated into the overlying diamict (**Fig. 3.4B**). The lobate-shaped diamict unit (**Fig. 3.3**) is interpreted as a subaqueous slump/debris flow which may have been released from the subaqueous channel wall.

Throughout the Bluffs region the amount of deformation in sediments underlying the Sunnybrook is considered to be very slight (c.f. Aber, 1993). In sections visited along the Bluffs, those in the CFA exhibit more complex and slightly greater depth of deformation (CFA: up to 2.0-2.5m below contact) than those in the HFA (<1.3m below contact; **Fig. 2.23**). Several types of deformation are observed in sediments underlying the CFA, including low and high angle faulting, and loading structures. The origin of deformation of the Scarborough Formation below the CFA is probably related to both the formation and the infilling of channels. Loading structures caused by the imposition of overlying Sunnybrook and Pottery Road Formation, are observed within the uppermost Scarborough.

3.2 HIGH FACIES ASSOCIATION (HFA)

3.2.1 GENERAL

The High Facies Association (HFA) of the Sunnybrook exposed along the Bluffs consists of an association of massive 'rain-out' diamicts (Dmm facies), stratified diamicts (Dms facies), and deformed laminated silts and clays (Fl(df) facies). In addition, the HFA is characterized by common basal clast horizons, an interbedded basal contact zone, and reverse density loading along the upper contact of the Sunnybrook with the Lower Thorncliffe Formation (**Table 3.4**).

section no.	facies association	basal clast horizon	I.C.Z.	loaded upper contact	graded upper contact
9301	HFA	X	X	X	
9303A	CFA				X
9303B	CFA				X
9311	CFA			o	o
9313	HFA	X	X	X	
9314	HFA	X	X	o	o
9314A	HFA	X	X	o	o
9315	CFA			o	o
9317	HFA	X	X	X	
9318	CFA		X	o	o
9320	HFA		X	o	o
9323	HFA	X		o	o
9324	rouge			X	
9325	HFA	X	X	X	
9326	rouge		X	o	o

Table 3.4: Sedimentological characteristics of the Sunnybrook's two facies associations. The HFA is generally characterized by an interbedded basal contact (ICZ) with underlying Scarborough sands, a basal clast horizon, and reverse-density loading along the upper contact with overlying Thorncliffe sands. The CFA is characterized by the absence of the ICZ and basal clast horizons and by the presence of gradational upper contacts. For each section, an "X" indicates that the characteristic is present; an "o" indicates a 'post-Sunnybrook' erosional contact (i.e. with either Halton Till or Lake Iroquois deposits).

The HFA is defined for sections along the Bluffs located on the relative highs between channels; highs are located west of Fishleigh Drive (section 9315), between Cathedral Bluffs and Sylvan Park sections (9313 and 9301), and east of the Guild Inn (section 9311; **Fig. 3.1**). Measured elevations of the Sunnybrook contacts for sites within the HFA along the Bluffs suggest a relatively constant elevation for the basal (≈113m) and upper (≈122m) contacts (**Table 3.1**); contact elevations for Rouge sections are slightly higher at 114m and 125m respectively. The basal contact of the Sunnybrook HFA with underlying Scarborough Formation sediments is essentially planar (**Fig. 2.27**). The upper contact of the Sunnybrook HFA with the overlying Thorncliffe Formation sands is always abrupt and can either be sharp and planar or undulating with up to 2m of relief caused by reverse density loading of the sands into the underlying diamict (**Figs. 2.30** and **2.31**). This sharp upper contact contrasts to the gradational contact observed between the Sunnybrook and the Thorncliffe Formation within the CFA (see **Fig. 2.13**).

3.2.2 FACIES OF THE HFA

The drape of Sunnybrook diamict on relative highs along the Bluffs is typically 5 to 7m thick (**Table 3.2**) and comprises predominantly massive diamict facies (**Fig. 3.5**). Massive diamict facies are interbedded with thin units of stratified diamict (<0.5m thick) and also contain isolated fine sand and silt stringers (lithocode Dmm(sd,$); **Figs. 2.1a** and **3.5**). Diamict facies of the HFA exhibit a weak fining upwards trend (as demonstrated at Sylvan Park, section 9301; **Fig. 2.4**) with the lowermost Sunnybrook diamict having a higher sand content. Eyles (1982) and Hicock and Dreimanis (1992a) also identified a coarser-grained diamict, with numerous fine sand and silt stringers, at the base

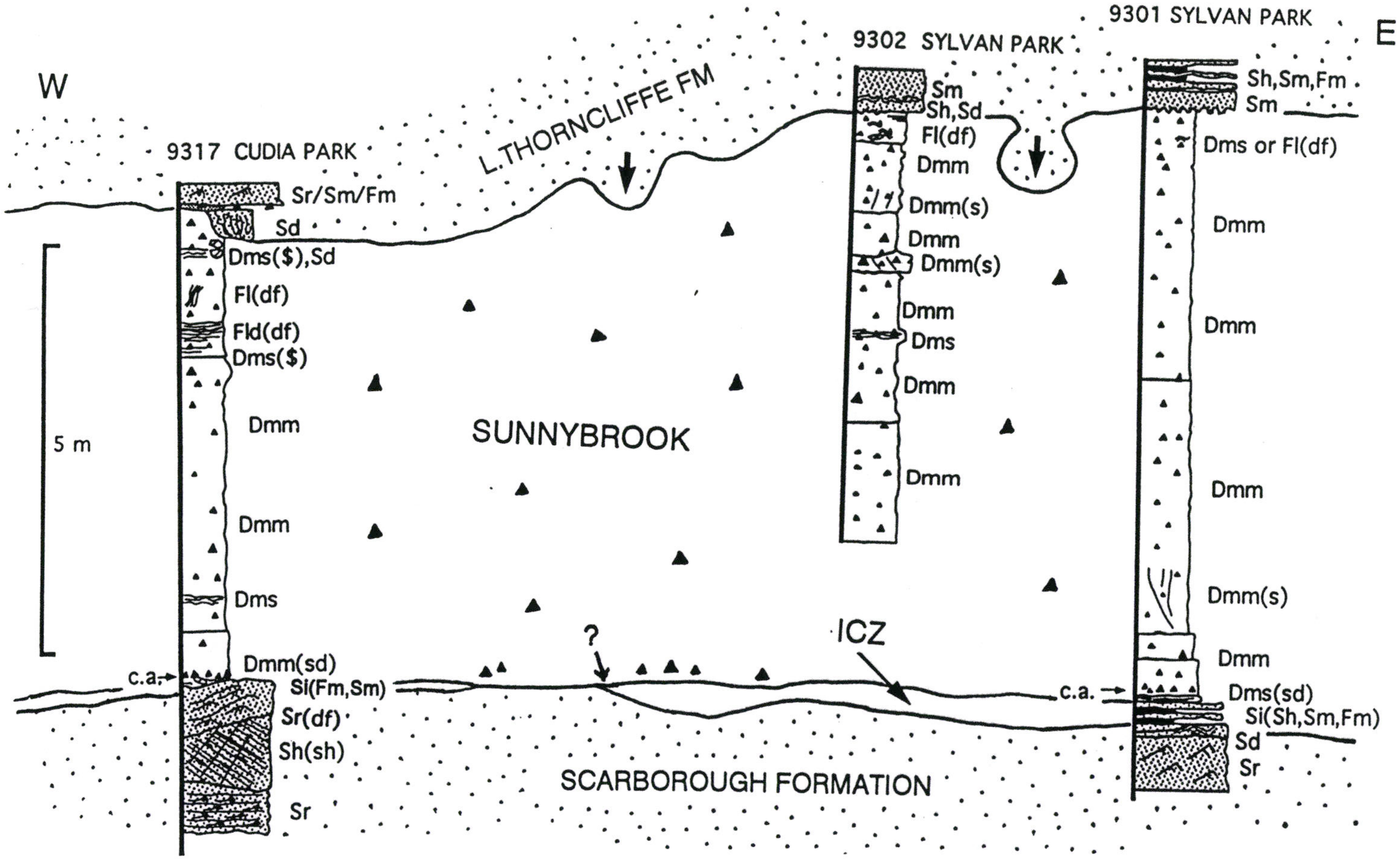


Figure 3.5: Sedimentological character of the HFA along part of the Bluffs between Cudia Park and Sylvan Park (sections 9317, 9302 and 9301; **Fig. 2.1a**). Massive diamicts show slight fining in matrix texture and clast content upsection. Basal contacts commonly consist of a zone of interbedded sand and laminated silt and clay (ICZ). Horizons of clasts (c.a.) close to the base of the diamict show an unorganized fabric although one clast horizon showed a weak to moderate preferential alignment of clast long axes in a NE-SW direction (section 9301; **Fig. 2.9**); there was no observable trend in striation directions on the upper surface of clasts.

of the Sunnybrook.

Basal clast horizons (discussed in section 2.1.3), generally one clast thick, are limited to the lowermost Sunnybrook diamict facies of the HFA along the Scarborough Bluffs, and coincide with occurrences of both the ICZ (**Table 3.4**) and the sharp change in sand content of the Sunnybrook diamict matrix (**Fig. 2.4**). Clasts within these horizons are cobble-sized, and have infrequently-striated tops. Clasts horizons show inconsistent fabrics; only one (of three) sites showed a weakly developed preferred NE-SW orientation of their major (a-) axes (**Fig. 2.9**). These clast horizons are conspicuously absent from diamict facies in the CFA. The model for formation of these horizons was discussed in section 2.1.3, and suggests they may have formed in a two step process involving the production of a clast lag, possibly by current winnowing of the substrate, and limited alignment/striation of clasts by grounding slabs of seasonal ice. These processes acted **only** during early Sunnybrook time and **only** on the relative highs. The lake was probably shallowest in early Sunnybrook time and allowed the winnowing of lake bottom sediments and the grounding of seasonal lake ice on relative highs on the lake floor. The lake probably deepened relatively rapidly as sand content in the diamict decreases rapidly upsection suggesting lower energy environments and increasing distance from a coarse-grained sediment source area.

An important characteristic of the HFA is that underlying Scarborough Formation sediments exhibit minimal deformation. In areas overlain by the HFA, the depth of deformation of the Scarborough Formation is generally less than one metre and commonly insignificant (i.e. no deformation found at sections 9320, 9314, 9314A, or 9301; **Fig. 2.23**). The type of deformation in sediments below the HFA is generally attributed to vertical loading of the interbedded contact zone which has caused some high angle (vertical) and micro-faulting in the uppermost Scarborough sediments (**Fig. 2.24**).

The uppermost HFA sediments are finer-grained and contain fewer clasts than other Sunnybrook diamict facies. They form a unit generally less than 1m thick (**Table 3.2**), which consists predominantly of deformed laminated silts and clays (Fl(df); **Fig. 2.18d**) and stratified diamicts (Dms; **Figs. 2.1a** and **3.5**). Some massive diamicts, containing evidence of resedimentation (e.g. flow noses and silt clast breccia), are found amongst these uppermost HFA facies (**Figs. 2.5** and **2.7a**).

The fine-grained nature of the uppermost HFA sediments within the Sunnybrook suggests that only fine-grained sediment was reaching these depositional sites in late Sunnybrook time. This may be a result of the focusing of coarser material in turbidites within the channels allowing only fine-grained 'overbank' sediments to reach the high areas. Localized slumping of the overbank facies within the HFA may have produced the deformed laminated facies within the uppermost Sunnybrook (e.g. **Fig. 2.18b**).

Large sand pillows (up to 2m in vertical extent) were identified within the HFA at the upper contact of the Sunnybrook with the overlying Lower Thorncliffe Formation along the Bluffs and in some creek exposures (**Table 3.4**).

In order to produce such large and extensive load structures, the uppermost Sunnybrook facies must have been highly water-saturated (Eyles, 1982) at the time of sand deposition; in addition, deposition of the Lower Thorncliffe sands must have occurred extremely rapidly (Clark, 1986). The delta which deposited the Thorncliffe sands advanced rapidly over the Scarborough area presumably because of lowered lake levels caused by the reduced height of the ice dam blocking the drainage outlet of the Lake Ontario basin.

3.3 SUNNYBROOK FACIES WITHIN THE CREEKS

The facies associations (CFA and HFA) discussed in the previous two sections were defined based on observations of Sunnybrook exposures along the Bluffs. Unlike exposures at the Bluffs, those in the dissecting creeks are rarely continuous and the basal contact of the Sunnybrook is infrequently exposed, making it difficult to identify the topographic setting of the unit.

In areas north and east of the Bluffs, the Scarborough Formation thins, so that the Sunnybrook directly overlies bedrock and fills channels in the Duffins Creek Valley (Clark, 1986; N.Eyles, pers.comm., 1994). Exposures along Duffins Creek allowed Clark (1986) to describe a 'turbidite channel/basin fill' succession within bedrock channels similar to the CFA described at the Dutch Church Channel (**Fig. 3.6**). Moving westward from Duffins Creek, into the Rouge Valley, the Scarborough Formation thickens and shows a planar contact with the overlying Sunnybrook Formation (Rouge sections 9324 and 9326; **Fig.**

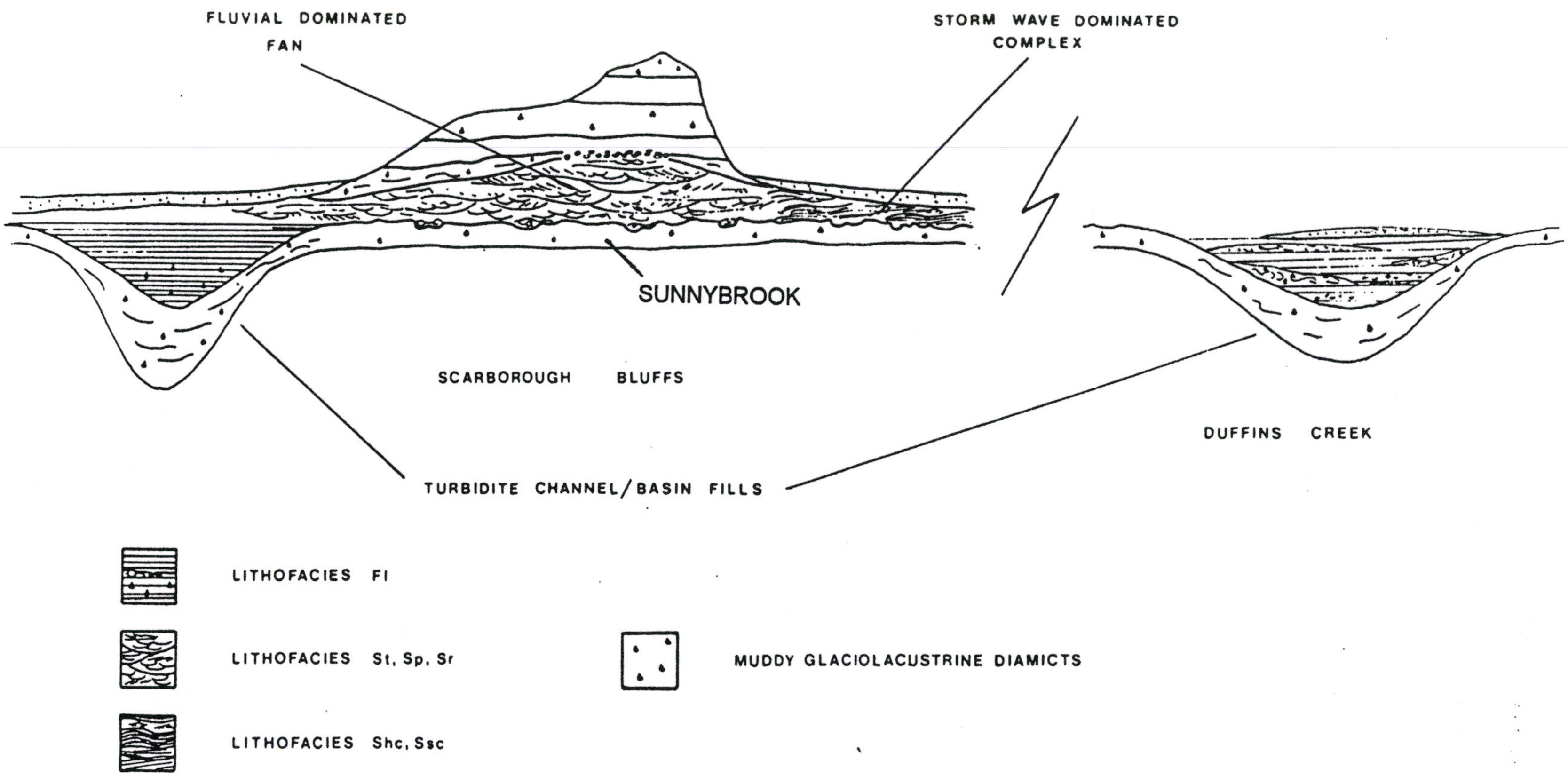


Figure 3.6: Depositional model for the Lower Thorncliffe Formation (from Clark, 1986). A sequence of turbidites overlying glaciolacustrine diamicts of the Sunnybrook is capped by a rapidly prograding delta (Lower Thorncliffe Formation) which advanced in a southerly-southeasterly direction over the Scarborough area. Turbidite channel fills have gradational contacts with overlying 'fluvial dominated fan' sediments or the 'storm wave dominated complex' of the Thorncliffe Formation. Away from the channels, on the relative highs, the Thorncliffe sands are loaded into underlying Sunnybrook diamict.

2.1b). In the Rouge, the most common facies types are deformed laminated facies and stratified and massive diamicts (**Fig. 2.1b**), with only a small (but important) component of undisturbed laminated facies; undisturbed laminated facies were found within diamict facies (section 9324) and represent 'quiet' rain-out of silt and clay in a predominantly glaciolacustrine environment. Abundant deformed laminated facies in Sunnybrook outcrop in the Rouge Valley suggest downslope slumping of beds (**Figs. 2.7b** and **2.18a,b**). These features and the absence of clast horizons and an interbedded contact zone give support to the interpretation of the Rouge and Duffins sections as belonging to the CFA.

3.4 OTHER SITES NOT VISITED

The Sunnybrook diamict has been identified at many sites in the Toronto area, some of which are no longer accessible. Positive identification of the Sunnybrook away from the Scarborough Bluffs is based on the identification of a number of criteria. The most reliable means to identify the Sunnybrook is on the basis of its stratigraphic position between two distinctive units (e.g. the underlying organic-rich Scarborough Formation and the overlying silty-sands of the Thorncliffe Formation; Eyles, N. et al., 1985; Kelly and Martini, 1986). In other studies, matrix texture, clast content, and 'blocky' weathering patterns (Westgate et al., 1987) have helped to identify Sunnybrook in creek sections and drill core. Eyles, N. et al. (1985) used geophysical well logging techniques to map out the inland (northern) extent of the units exposed along the Bluffs; they

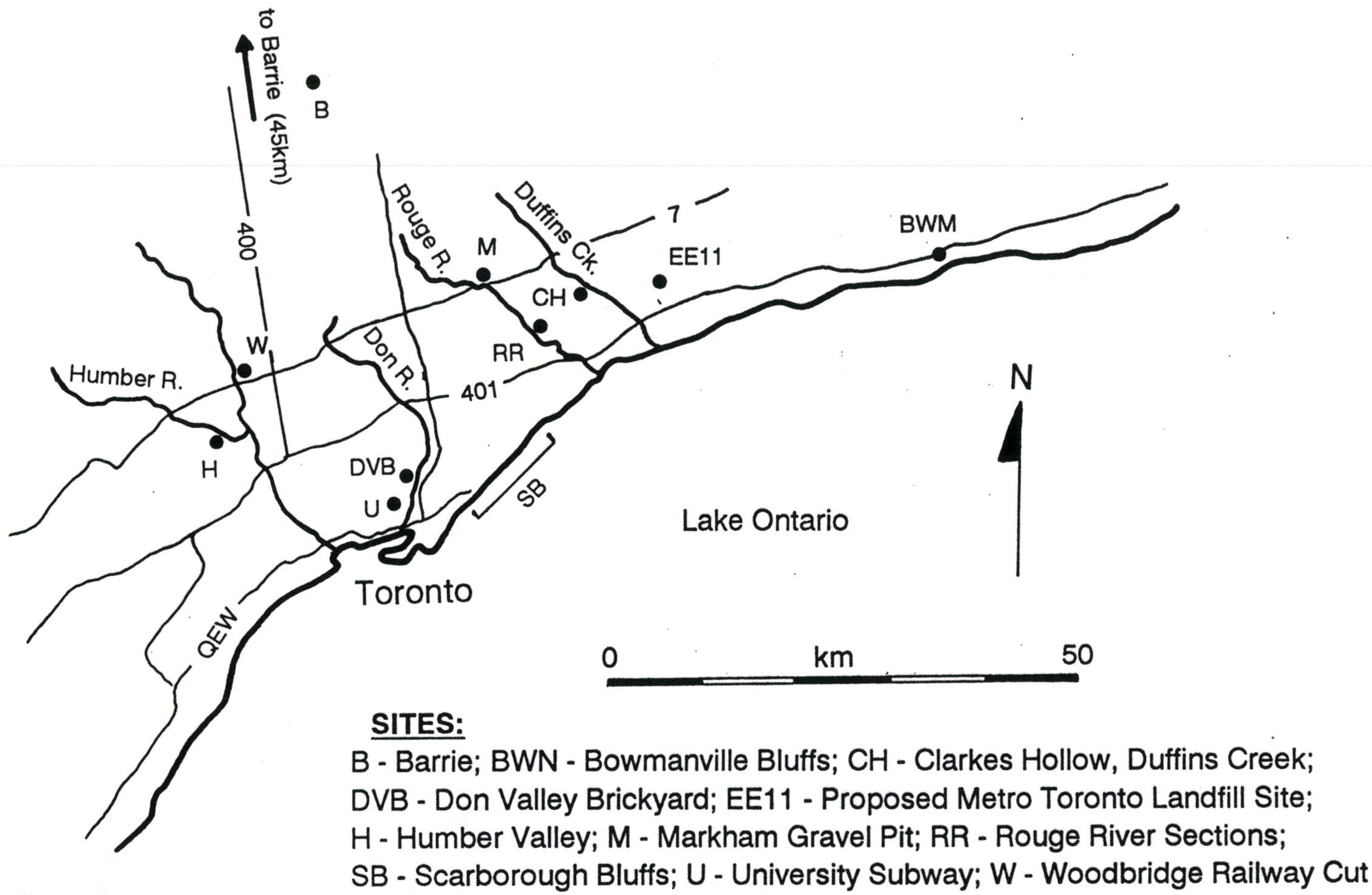


Figure 3.7: Sites of known Sunnybrook outcrop, including those visited (SB, RR, and CH) and not visited (H, W, B, DVB, U, M, B and BWN) in this study. Locations of unvisited sites are those shown in figure 10 of Hicock and Dreimanis (1992a). Location of the proposed landfill for Durham Region is shown as site EE11.

were able to trace the Sunnybrook and the Scarborough Formation close to Barrie (65km north of Toronto; **Fig. 3.7**). Ongoing investigations of a proposed landfill site for Metro Toronto in Durham Region, adjacent to Duffins Creek (the EE11 site; **Fig. 3.7**) have identified Sunnybrook diamict in core (Joe Boyce, pers.comm., 1994). Data available suggest the Sunnybrook consists of fine-grained massive diamict facies sitting in topographic depressions (bedrock channels, see section 3.3 above; N.Eyles, pers.comm., 1994), and has characteristics similar to facies of the CFA.

Probably the most well-known site exposing Quaternary age deposits in the Lake Ontario basin is the Don Valley Brickyard (DVB; **Fig. 3.7**), type section for the Don Formation which records environmental conditions during the last interglacial period in this area (Eyles and Clark, 1988a; Karrow, 1989). The Wisconsin stratigraphy of the DVB site comprises the Scarborough Formation, dissected by a large channel (up to 1km wide and 70m deep; Eyles and Clark, 1988a), which is infilled by crudely bedded sands and gravels of the Pottery Road Formation, and a 10m thick package of interbedded diamict, sand and laminated silt and clay facies of the Sunnybrook. The uppermost Sunnybrook deposits consist of laminated silty clays. This package of facies clearly resembles the Channel Facies Association described in section 3.1.

Subsurface studies made during the construction of Toronto's subway network (Watt, 1954; Lajtai, 1969), identified "varve-like" sediments overlying a 'clayey-till', which Lajtai (1969) correlated to the Sunnybrook at the Bluffs.

These deposits probably also belong to the CFA. This is not surprising as most of Toronto is underlain by a large bedrock channel forming part of the Laurentian River system (Spencer, 1890; Eyles, N. et al., 1985; **Fig. 3.2**). Elevations of the basal contacts measured at the DVB and during excavation of Toronto's subway range from 80 to 100 m.a.s.l., and are similar to contact elevations found for the CFA (**Table 3.5**). These elevations are further evidence that these sites sit within topographic lows in the substrate and that their sediments belong to the CFA.

Other sections of exposed Sunnybrook have been described at Woodbridge railway cut (White, 1971), Humber River (Hicock and Dreimanis, 1992a), and the Markham gravel pit (Dreimanis and Terasmae, 1958). Detailed sedimentological descriptions of these three sites are not available, but general interpretations of Sunnybrook facies types (diamict or laminated) present at the sections can be inferred (**Table 3.5**). North of the Bluffs, at these three sites indicated, only massive diamict facies have been described by Hicock and Dreimanis (1992a) and the basal contact elevation ranges from 140 to 155 m.a.s.l. (**Table 3.5**). These facies and elevation characteristics of the Sunnybrook resemble those of the HFA along the Bluffs and suggest the loss of the CFA moving inland from the Lake Ontario shoreline. The profile of the top of the Scarborough Formation (presented by Eyles, N. et al., 1985) shows increasing elevation of the delta top moving towards Barrie and corroborates the idea that the CFA is limited to topographic lows found closer to the Bluffs.

location	basal contact elevation (m.a.s.l.)	Fl facies	Dmm facies	ICZ
Bluff CFA[1]	<75-105	X	X	-
Bluff HFA[1]	109-118	-	X	X
Rouge River[1]	112-116	-	X	-
Rouge River[2]	120	X	X	X
Scarb.Delta Top (Bluffs)[2]	114-119	(X)	X	(X)
Don Valley Brickyard[2]	97-100	X	X	-
Woodbridge[2]	140	-	X	-
Humber River[2]	149	-	X	-
Markham Gravel Pit[2]	155	-	X	-
University Subway[3,2]	80-100	(X)	(X)	(X)

Table 3.5: Summary of Sunnybrook characteristics noted at various locations in the Toronto area. The elevation of the basal contact is indicated in metres; current level of Lake Ontario is 75 m.a.s.l.. Sedimentological criteria (Dmm and Fl facies and the Interbedded Contact Zone) are either everywhere present [X], absent [-], or absent in some sections [(X)]. Sources of data are indicated by the suprascripts: 1=this study; 2=Hicock and Dreimanis (1992a); 3=Lajtai (1969). Hicock and Dreimanis (1992a) and this study did not sample the same sections in the Rouge River; their 'Scarborough Delta Top' sections are located near to those of to the HFA of this study; the bottom five rows in the table are data summarized by Hicock and Dreimanis (1992a).

To the east of Toronto, sediments exposed within the Bowmanville Bluffs have been stratigraphically correlated to the units within the Scarborough Bluffs by Singer (1974) and Brookfield et al. (1982). Units 1 and 2 (of Brookfield et al., 1982) are thought to correspond to the diamict and laminated facies types of the Sunnybrook's CFA. Laminated facies (unit 2), overlying massive and stratified diamicts, are sedimentologically similar to the laminated facies of the

Sunnybrook CFA. Beds in the lower portion of the unit contain diamict clots and 'glacial silt debris' (i.e. silt clast breccia) and are locally deformed - presumably by subaqueous slumping. Laminated beds, moving upsection, show variable thickness (15 to 95 cm) and grade from thin sand beds or climbing rippled sands to silt and a clay cap. These are presumably turbidites. The Port Hope diamict (unit 1; Brookfield et al., 1982) has been interpreted as a subglacial deposit (Brookfield et al., 1982) but is closely associated with overlying laminated facies (unit 2), and may in part be of glaciolacustrine origin. According to Brookfield et al. (1982, p.1840), "the character of the Port Hope diamict and its contact with the varved portion of the overlying unit indicate it was deposited from an ice sheet grounding at the margin of a large lake".

3.5 DEPOSITIONAL MODEL

This study is not the first to advocate a subaqueous depositional environment for the Sunnybrook. The results of this study support previous glaciolacustrine interpretations made by Eyles and Eyles (1983) and Clark (1986), and have allowed the development of a more detailed depositional model for the Sunnybrook. Specifically, the proposed model includes two newly defined facies associations (e.g. CFA and HFA) and provides preliminary models for the development of basal clast horizons, and for the limited deformation observed within the underlying Scarborough Formation (see section 2.3.1). A number of diagnostic criteria have been identified for each of the two facies associations so that sediments belonging to each may be identified in outcrops where the topographic setting is uncertain (**Table 3.4**). This was shown to be useful in identifying the CFA in outcrop in the Rouge River Valley on the basis of two criteria: 1) the topographic position of the Rouge Valley within a bedrock low, and 2) the common presence of resedimentation structures in the diamict facies (see section 3.3). These two associations should be useful in making correlations with other outcrops away from the Scarborough area (e.g. Bowmanville Bluffs).

The present study has found sedimentological evidence to support rain-out (e.g. from suspension and ablating ice bergs) and resedimentation processes (e.g. subaqueous slumps, turbidity currents, density underflows) as the main agents responsible for the deposition of the Sunnybrook, which are described below.

3.5.1 DESCRIPTION

The depositional model depicted in **Figure 3.8** identifies three groups of depositional processes, each of which is responsible for distinct facies characteristics within the Sunnybrook.

The first group of processes operates on the relative highs of the substrate and results in the development of the HFA. Diamict accumulation occurs as a result of 'rain-out' of fine-grained sediment from plumes of suspended fines carried into the basin by meltwaters emanating either from the ice margin or from glaciofluvial sources (A: **Fig. 3.8**) and coarser debris supplied by ablating ice bergs (C: **Fig. 3.8**). On the substrate highs, water depths are relatively low during initial diamict accumulation and allow currents generated by wind and/or wave action to periodically winnow and redistribute sediment. This results in the development of an interbedded contact zone (ICZ: E on **Fig. 3.8**) where thin beds of diamict are interspersed with thin units of massive and rippled sands (e.g. **Fig. 2.28**). Winnowing of accumulating diamict by traction currents also results in the formation of clast lags (F: **Fig. 3.8**) which may be overridden by grounding masses of seasonal ice (G: **Fig. 3.8**) to produce basal clast horizons. Given that winnowing processes are restricted to 'highs' on the basin floor where relatively shallow water conditions existed, features such as the ICZ and basal clast horizons are found only as part of the HFA (see section 3.2). These features are blanketed by 'rain-out' and resedimented diamict on the highs as water depths increase in the basin.

The second group of depositional processes is responsible for the accumulation of thick diamict units in lows on the underlying deltaic surface (CFA: see section 3.1). The lows or channels on the substrate may have originated as growth faults or slump scars on the rapidly prograding delta; slight downslope movements within the surrounding deltaic sediments probably resulted in the formation of soft sediment deformation structures (H: **Fig. 3.8**) which are now visible below the Sunnybrook. Diamict accumulating on the basin floor as a result of 'rain-out' processes is highly water saturated and unstable even on relatively low angle slopes and will be extremely susceptible to downslope slumping. Diamict will therefore tend to be focussed into lows on the substrate through gravity-induced resedimentation processes (I: **Fig. 3.8**). This redistribution of diamict facies is reflected in the occurrence of thicker diamict units in the CFA than in the HFA (**Fig. 3.8**).

The final group of processes is associated with the accumulation of laminated facies on top of resedimented diamicts in the topographic lows. Laminated facies are formed as a result of deposition from turbidity currents and density underflows which were focused into lows on the basin floor (see section 2.2.1; J,K: **Fig. 3.8**). These currents and underflows were probably generated on the oversteepened and unstable subaqueous slopes of a delta body advancing into the lake (Thorncliffe Delta: L: **Fig. 3.8**). Instabilities of the diamict along the margins of these lows is indicated by the occurrence of thin diamicts deposited as debris flows within the laminated facies (M: **Fig. 3.8**).

One problem with the depositional model for the Sunnybrook presented in **Figure 3.8** is the uncertainty of the position and extent of the ice margin in the basin at the time of Sunnybrook deposition. An ice sheet margin lying to the north and east of the Scarborough Bluffs area is inferred because the Sunnybrook shows no facies associated with ice proximal depositional conditions (c.f. Powell and Molnia, 1989). Glacier ice is present **somewhere** in the basin, however, to provide an abundant sediment supply both from ice bergs and from meltwater plumes.

A second problem with the depositional model lies in determining the size and extent of the lake in which the Sunnybrook was deposited. There are no preserved shoreline facies or geomorphic features relating to Sunnybrook time as these have been removed by post-Sunnybrook erosional processes. More detailed subsurface investigations of the lateral facies variability of Sunnybrook facies to the north and east of the Bluffs region may be necessary to resolve both of these problems.

3.6 CONCLUSION

In conclusion, there are two facies associations proposed for the Sunnybrook along the Scarborough Bluffs: Channel (CFA) and High (HFA) Facies Associations (**Fig. 3.1**). Diagnostic criteria for the CFA are its topographic position in lows in the underlying strata, whether they be channels cut into the Scarborough Formation or channels in the underlying bedrock, and the predominance of massive and stratified diamicts conformably overlain by laminated silt and clay turbidites. The total thickness of the CFA can be in excess of 50 m (e.g. at the Dutch Church channel; **Fig. 2.1a**). Increasing sand content within the laminated facies is linked to the approaching influence of the Thorncliffe delta body (Clark, 1986).

The High Facies Association (HFA) of the Sunnybrook occurs on the relative highs along the Bluffs (**Fig. 3.1**), and consists of a 5 to 7m thick drape of massive and stratified diamict facies. It has distinctive sedimentological characteristics that include basal clast horizons and an interbedded basal contact zone. Upper portions of the Sunnybrook within the HFA are finer grained (**Fig.**

2.4) and may be laterally correlated to the laminated facies of the CFA. The upper contact of the HFA is loaded by sands of the Lower Thorncliffe Formation, which give evidence that the diamict facies were water-saturated and unconsolidated at the time of rapid delta encroachment over the area.

Observations of the facies and contacts of the Sunnybrook suggest that the depositional environment at the Scarborough Bluffs was characterized by rain-out and resedimentation processes in a large glacial lake. Resedimentation processes, including subaqueous slumps and debris flows and turbidity currents, are the predominant means of depositing the CFA; the dominant process depositing the HFA is rain-out from ablating icebergs, with limited re-sedimentation in early and late Sunnybrook times. Subglacial and ice-proximal environments, synchronous to subaqueous environments at Scarborough, are presumably located far north and east of the Bluffs, although the exact position of the ice sheet margin has not been determined. Locating facies from these sediments is hampered by post-Sunnybrook erosional events (e.g. Halton ice, glacial lake Iroquois).

CHAPTER 4:
DEPOSITIONAL HISTORY OF THE SUNNYBROOK

4.0 INTRODUCTION

Facies and facies associations described in the two previous chapters were used to infer a subaqueous depositional model for the Sunnybrook (**Fig. 3.8**). In this chapter, the changing environmental conditions which occurred during the time of Sunnybrook deposition are described. The depositional history will be presented in four sections, each referring to a major change in depositional environment: 1) upper Scarborough Formation and origin of channels; 2) lower Sunnybrook; 3) middle and upper Sunnybrook; and 4) lower Thorncliffe Formation.

4.1 DEPOSITION OF THE UPPER SCARBOROUGH FORMATION and THE ORIGIN OF CHANNELS

The Scarborough Formation was deposited as a delta during the early Wisconsin by a large river which connected the Lake Huron and Lake Ontario basins (**Fig. 4.1a**). Progradation of the delta into Lake Ontario is recorded by the coarsening upwards succession of muds and sands within the Scarborough Formation (see descriptions of Clark, 1986 and Kelly and Martini, 1986); trough and planar-crossed bedded sands in the upper Scarborough Formation represent

a) plan view

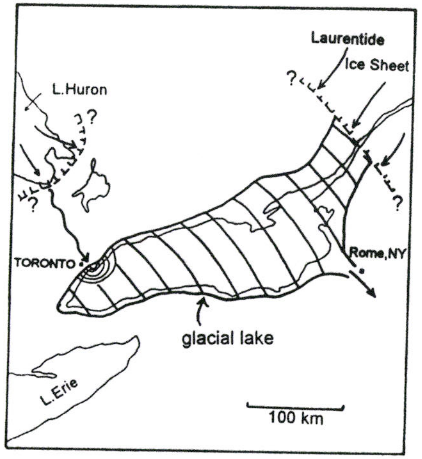
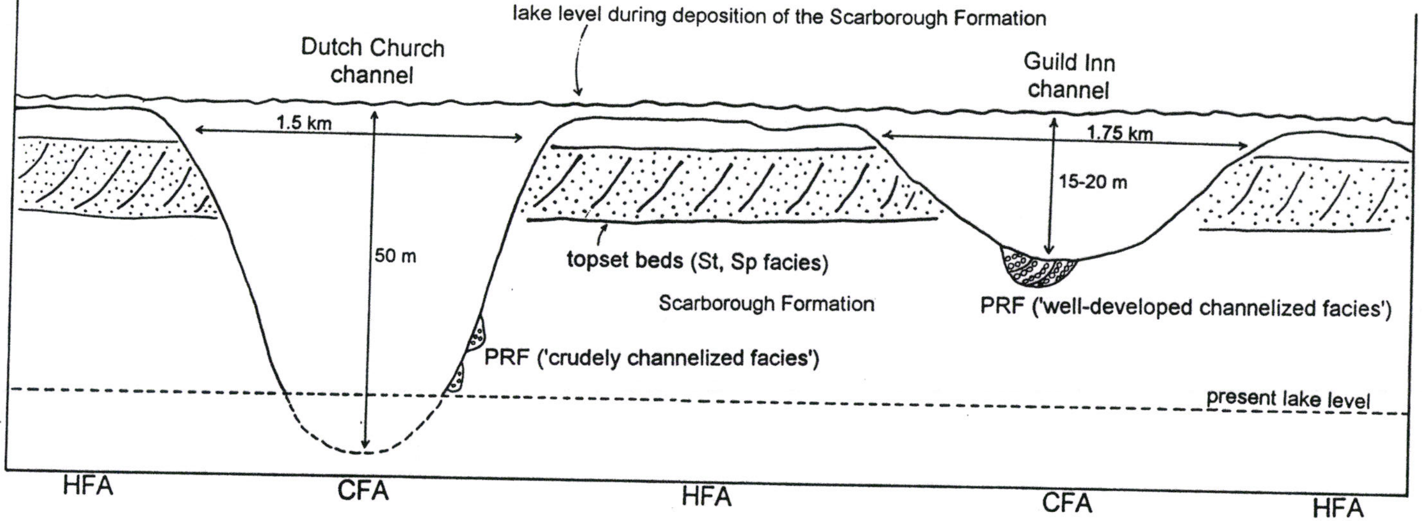


Figure 4.1: Deposition of the upper Scarborough Formation and the form of channels cut into the Scarborough Formation. **a)** shows a plan view of ice sheet positions and the extent of the glacial lake in the Lake Ontario basin; the lake drained through the outlet at Rome, NY. Ice sheet margins are dashed as their precise locations are unknown. **b)** shows a cross-section along the Bluffs indicating channel dimensions and the position of Pottery Road Formation (PRF) sediments within the channels. Lake level during deposition of the Scarborough Formation is indicated.

b) cross-section



the delta's topset beds (**Fig. 4.1b**). The elevation of these topsets is approximately 40m above the present lake level and therefore, the depth of Lake Ontario during deposition of the Scarborough Formation was at least 40m above present lake levels. Elevated lake levels during period were caused by the blockage of the normal drainage outlet, in the St. Lawrence Valley, by a lobe of the Laurentide ice sheet. The lake was drained through a higher elevation outlet at Rome, New York (**Fig. 4.1a**).

The origin of channels on the upper surface of the Scarborough delta is controversial. Channels may have been cut as part of a shifting distributary channel network on the prograding delta (e.g. 10-20m deep; Guild Inn channel) with some fluvial gravels deposited at the base of these channels (Pottery Road Formation: PRF). Larger channels (e.g. ≈50m deep; Dutch Church channel) are too deep to be distributary channels and probably formed as large subaqueous slumps or growth faults along the delta margin. This slump-generated model for formation of the large channels is supported by the presence of limited deformation of the Scarborough Formation sediments adjacent to channels and by the deformed 'crudely channelized' character of the PRF in larger channels. Channel formation occurred immediately prior to deposition of the Sunnybrook diamict suggesting that slumping events may have been triggered by changing lake levels or earthquake shocks generated by isostatic movements as ice advanced into the basin.

Fossil material within the Scarborough Formation provides evidence of deteriorating climatic conditions in eastern North America during the early Wisconsin (Terasmae, 1960; Morgan and Morgan, 1976; Williams et al., 1981; Eyles and Williams, 1992). Eyles and Williams (1992; see their figure 9) concluded that the youngest Scarborough deltaic sediments, lying immediately below the Sunnybrook, were deposited in a subarctic climatic regime having local mean annual temperatures at least 7°C lower than present; these cooler climates presumably led to the advancement and thickening of the Laurentide ice sheet. An ice dam is thought to have blocked lake drainage through the St. Lawrence Valley during the early Wisconsin resulting in higher lake levels in the Ontario basin which flooded the top of the Scarborough delta and caused the Scarborough delta to regress northward. This increase in water levels at the Scarborough Bluffs would starve the delta of its supply of coarse (sandy) sediment and deposition of suspended fines would begin to dominate. The gradual diminishing sand content as mud deposition began to dominate was noted in descriptions of the upper 2m of the Scarborough Formation and the Interbedded Contact Zone (ICZ; section 2.3.3). Moving upsection, planar bedded sands (Sp) of the Scarborough Formation gave way to rippled sands with substantial mud content (Sr; **Fig. 4.2b**). With continued delta regression, laminated muds were interbedded with periodically current-deposited sands, together referred to as the ICZ. The contact (e.g. ICZ) between the sands of the Scarborough Formation and lowermost muddy diamicts of the Sunnybrook thus primarily reflects changing water depths in the Ontario basin.

4.2 DEPOSITION OF THE LOWER SUNNYBROOK

During deposition of the lower Sunnybrook, shallow lacustrine conditions persisted on the relative highs along the Bluffs and deeper lacustrine conditions persisted in the topographic lows or channels (**Fig. 4.2b**).

Relatively shallow water conditions are recorded in lowermost Sunnybrook deposits of the HFA. At these sites the ICZ records winnowing and redistribution of sediments by traction currents and striated clast horizons reflect periodic grounding of seasonal ice masses on the highs (**Figs. 3.8** and **4.2b**). Moving upsection within the Sunnybrook evidence for current winnowing diminishes and diamict accumulation predominates. Earliest Sunnybrook deposition in channels along the Bluffs consisted of quiet 'rain-out' of suspended fines. These muds probably did not amount to significant accumulation and were later re-worked by subaqueous resedimentation processes.

Advance of the Laurentide ice sheet into the Ontario basin during early Sunnybrook time probably released copious amounts of meltwater and large ice bergs which rafted clasts and coarser-grained sediments far into the basin allowing widespread diamict deposition to occur. Advance of the continental ice sheets is inferred from oxygen isotope ratios derived from marine benthic foraminifera (Martinson et al., 1987; decrease in $\delta^{18}O$ at the beginning of stage 5; **Fig. 1.4**). Because the decrease in $\delta^{18}O$ is smaller than in the late Wisconsin, it is postulated that this advance of the LIS was smaller in areal extent than the maximum advance in the late Wisconsin in the Ontario basin (Eyles and

a) plan view

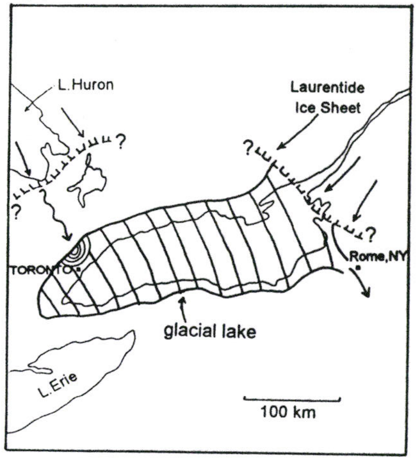
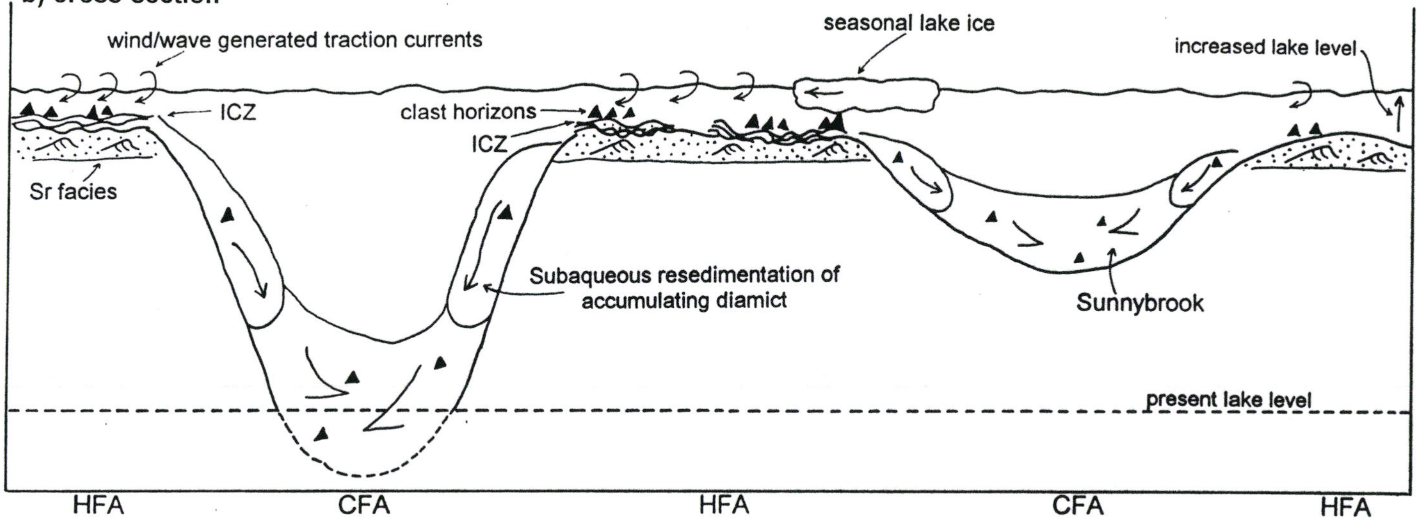


Figure 4.2: Deposition of the lower Sunnybrook, including the Interbedded Contact Zone (ICZ) and basal clast horizons, and Sr facies of the upper Scarborough Formation. **a)** shows a plan view of approximate ice sheet positions (dashed lines) and the extent of the glacial lake in the Lake Ontario basin. During deposition of the Sr facies, ICZ, and the lower Sunnybrook diamict, the Scarborough delta migrated northward. **b)** shows a cross-section along the Bluffs of the processes which produced basal clast horizons and the ICZ on the relative highs (HFA) and resedimentation of accumulating diamict to topographic lows (CFA).

b) cross-section



Westgate, 1987), and thus that ice did not override the Scarborough Bluffs area.

As the Laurentide ice sheet advanced across the eastern end of the Lake Ontario basin and blocked the Rome outlet of the lake, levels were increased further and drainage of the lake southward into the Mississippi basin occurred (**Fig. 4.3a**). Raised lake levels eliminated the affects of wind/wave generated traction currents and of seasonal lake ice on lake bottom sediments, and hence the deposition of clast horizons and sand lenses in the Sunnybrook diamict ceased (**Fig. 4.3b**).

4.3 DEPOSITION OF MIDDLE AND UPPER SUNNYBROOK

During deposition of the middle and upper Sunnybrook, the level of the lake was probably relatively constant, with water depths controlled by the outlet at the southwestern corner of the lake (**Fig. 4.3a**). Ostracod valves within the Sunnybrook suggest deep lacustrine conditions (lake depths in excess of several 10's of m; *Candona species*: **Table 1.4**) during most of the Sunnybrook interval (Rutka and Eyles, 1989). During this time widespread deposits of diamict accumulated on the lake floor by rain-out and resedimentation processes as discussed in section 3.5 (**Fig. 4.3b**). Shallower lake depths (<20m) in mid- to late Sunnybrook time are inferred from the presence of shallow, warmer-water ostracods (*Darwinula stevensoni*; **Table 1.4**; Rutka and Eyles, 1989). Much of the ice had probably retreated from the Ontario basin, leading to lower lake levels and warmer climatic conditions. Marine oxygen isotope data reflects a recession

a) plan view

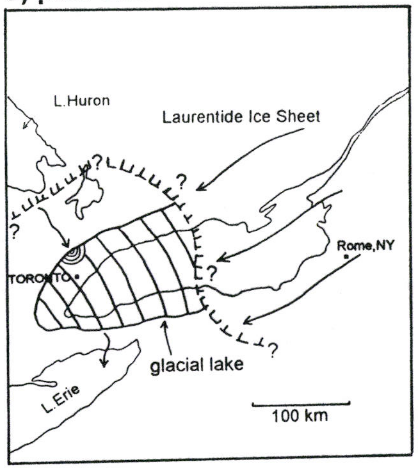
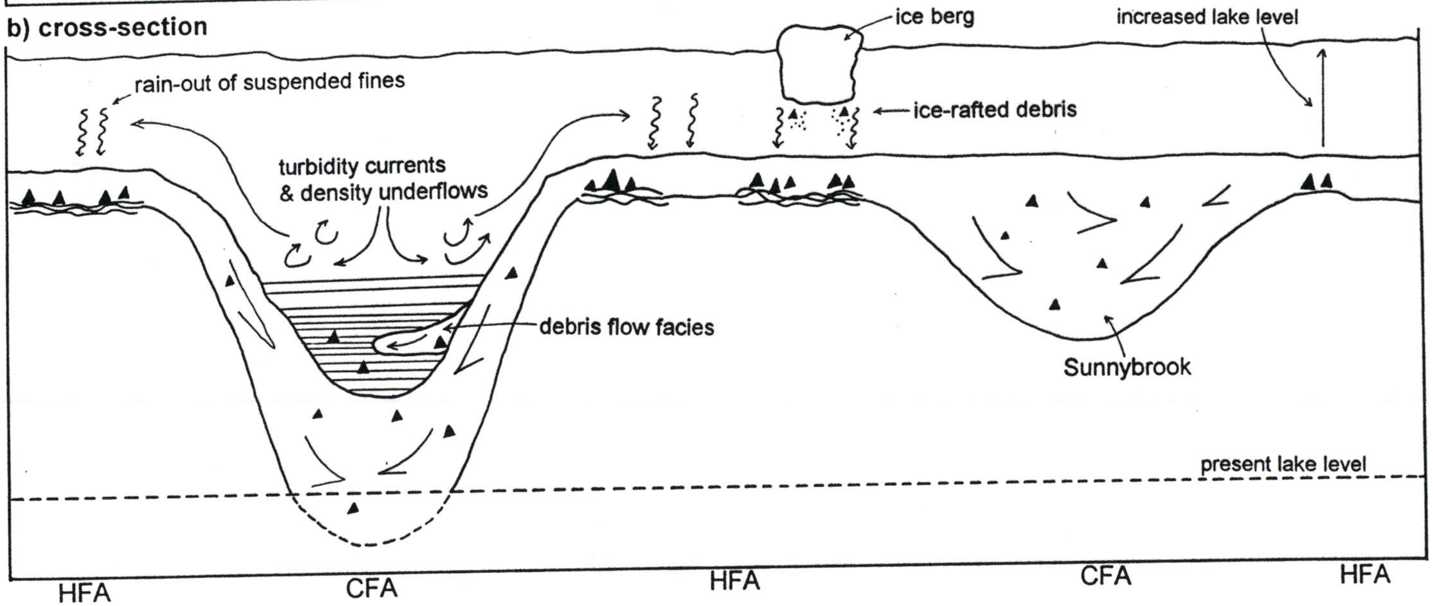


Figure 4.3: Deposition of the middle and upper Sunnybrook, including diamict and laminated facies. **a)** shows a plan view of approximate ice sheet positions (dashed lines) and the extent of the glacial lake in the Ontario basin. At its highest level, the lake drained southward into the Mississippi drainage. **b)** shows a cross-section along the Bluffs of 'rain-out' and resedimentation processes which deposited the middle and upper Sunnybrook. Diamicts of the HFA accumulated by rain-out from suspended sediment and from ablating ice; those of the CFA accumulated through rain-out as well as via subaqueous slumping of unstable diamict slopes along the channel walls. Laminated facies of the CFA and fine-grained clast poor diamicts of the HFA were deposited by turbidity currents and density underflows which travelled along channel axes.

b) cross-section



of continental ice sheets in late Sunnybrook time as suggested by an increase in the $\delta^{O}18$ content of marine forams (end of oxygen isotopic stage 5; **Fig. 1.4**). During these later phases of Sunnybrook deposition the amount of ice rafted (coarse) material and suspended fines to the region was reduced resulting in clast poor diamicts accumulating on the highs and deposition of laminated facies from turbidity currents and density underflows in the lows (**Fig. 4.3b**). These turbidity currents and density underflows were probably initiated on the subaqueous delta front of the Thorncliffe delta which advanced into the Lake Ontario basin during late Sunnybrook time (**Fig. 3.8**). The reduction in ice-rafted debris (IRD) and suspended fines supplied to the region probably reflects reduced ice volumes and a withdrawal of Laurentide ice from the basin. As the ice margin withdrew from the periphery of the basin a significant subaerial drainage network could be re-established north of Toronto which fed the Thorncliffe delta (**Fig. 4.3a**). Occasional icebergs were still rafting coarse-grained sediments and clasts during deposition of the lowermost laminated facies, but the influence of ice lessened through time and eventually ceased (i.e. IRD is absent in upper laminated facies; **Fig. 4.3b**).

Laminated facies were deposited only in topographic lows in the substrate. However, fine-grained sediments, put into suspension by turbidity currents and carried by lake currents, rained-out over the whole of the lake floor and produced finer-grained facies of the uppermost Sunnybrook on the highs (**Fig. 4.3b**).

4.4 DEPOSITION OF THE LOWER THORNCLIFFE FORMATION

Laminated facies deposited by turbidity currents and density underflows completely infilled the channels along the Bluffs. Sand content within these laminated facies increases upsection suggesting that the Thorncliffe delta was advancing further into the Lake Ontario basin towards the Scarborough Bluffs in late Sunnybrook time. The increased sand content of the Sunnybrook's laminated silts and clays (e.g. coarsening) is evidence of the transitional contact they have with the overlying Thorncliffe deltaic sands. A transitional/gradational contact implies **continuous** sedimentation in channels areas (**Fig. 4.4b**). Lake levels were probably lowered during deposition of the Lower Thorncliffe Formation and lake drainage through the Rome outlet was re-established (**Fig. 4.4a**). Sands deposited by the Thorncliffe delta in the central Bluffs area on the HFA show extensive loading into the underlying Sunnybrook diamict which indicates two things: 1) that diamicts were highly saturated at the time of sand emplacement, and 2) that the delta prograded rapidly over the Scarborough area and did not allow the diamict to de-water (**Fig. 4.4b**). Clark (1986) described facies of the Lower Thorncliffe Formation in the central Bluffs as the "fluvial dominated fan" of the delta (St, Sp, Sr lithofacies; **Figs. 4.4b** and **3.6**). In areas east and west of the central Bluffs, Clark (1986) described a "storm wave dominated complex" of the Lower Thorncliffe Formation, in which only high energy waves reworked nearshore sands and muds and generally produced gradational contacts with the underlying laminated Sunnybrook.

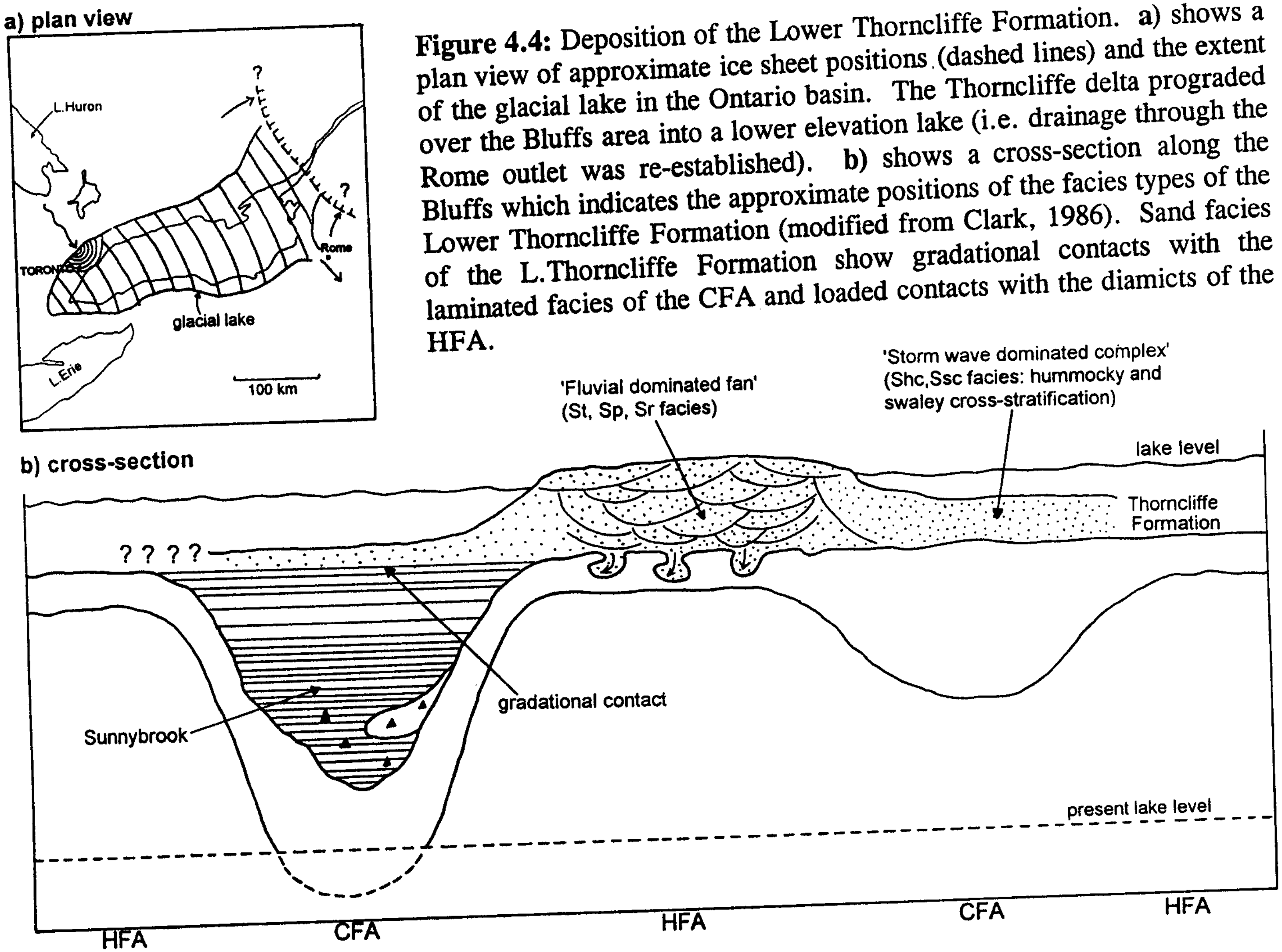


Figure 4.4: Deposition of the Lower Thorncliffe Formation. **a)** shows a plan view of approximate ice sheet positions (dashed lines) and the extent of the glacial lake in the Ontario basin. The Thorncliffe delta prograded over the Bluffs area into a lower elevation lake (i.e. drainage through the Rome outlet was re-established). **b)** shows a cross-section along the Bluffs which indicates the approximate positions of the facies types of the Lower Thorncliffe Formation (modified from Clark, 1986). Sand facies of the L.Thorncliffe Formation show gradational contacts with the laminated facies of the CFA and loaded contacts with the diamicts of the HFA.

4.5 CONCLUSION

The depositional history of the Sunnybrook is characterized by changing environmental conditions caused by initial deepening and later shallowing of water depths in the Lake Ontario basin caused by the thickening and then thinning of the ice dam which occupied the St. Lawrence Valley. The ICZ and basal clast horizons were formed in shallow lacustrine conditions in early Sunnybrook time; deeper lacustrine conditions followed in which diamict facies accumulated, with an ice sheet margin floating in the lake. In late Sunnybrook time, the Thorncliffe delta advanced into the basin and provided the source for a series of turbidity currents and density underflows that deposited the laminated facies in topographic lows in the substrate. Water depths were further lowered in the basin allowing the delta to advance over the entire Scarborough Bluffs area and deposit the Lower Thorncliffe Formation.

Overlying the Lower Thorncliffe Formation are two other fine-grained diamicts (Seminary and Meadowcliffe diamicts) which are interfingered with the Middle and Upper Thorncliffe Formations. The origins for these two diamicts, whose facies closely resemble those of the Sunnybrook (Eyles, C.H., 1982), are in glaciolacustrine environments with high lake levels formed by the blockage of the Rome and St. Lawrence outlets. The Middle and Upper Thorncliffe Formations represent re-advances of the Thorncliffe delta during episodes of reduced water depths.

The final events in the deposition of the Scarborough Bluffs succession are recorded by the Halton Till and Lake Iroquois deposits. In the late Wisconsin, the Laurentide ice sheet reached its maximum southern extent and deposited the Halton Till over the whole of the Lake Ontario basin. As ice retreated out of the Ontario basin to the east, a dam was again formed in the St. Lawrence Valley, forming a series of large glacial lakes, including Lake Iroquois.

CHAPTER 5: DISCUSSION

5.0 INTRODUCTION

The early to mid- Wisconsin history of the Scarborough Bluffs has been one of the most heavily debated issues in Quaternary studies in eastern North America during the 1980's. At the centre of the debate is a controversy concerning the depositional model which best suits the Sunnybrook diamict. Initially, the Sunnybrook diamict was interpreted as a grounded ice deposit (e.g. lodgement till; Karrow, 1967). A glaciolacustrine interpretation, first introduced by Eyles and Eyles (1983), generated much discussion and resulted in renewed interest from those inferring both subglacial (Dreimanis, 1984; Gravenor, 1984; Karrow, 1984a,b; Sharpe, 1984; Gravenor and Wong, 1987; Hicock and Dreimanis, 1989) and glaciolacustrine (Eyles and Eyles, 1987; Eyles and Westgate, 1987; Westgate et al., 1987; Eyles and Clark, 1988b; Rutka and Eyles, 1989; Schwarcz and Eyles, 1991) origins for the Sunnybrook. The evolution of more complex models of subglacial deposition (e.g. deformation till model; Boulton and Jones, 1979; Alley et al., 1987; Boulton and Hindmarsh, 1987) led others to reinterpret the Sunnybrook as a complex of both lodgement and deformation tills (Hicock and Dreimanis, 1992a). As a result of this intense debate over the origin of the Sunnybrook diamict, the present study was initiated in order to better evaluate the sedimentological characteristics of the unit.

The results this study have shown that a model evoking <u>subaqueous</u> rain-out and re-sedimentation processes in a glaciolacustrine environment affected by localized ice grounding on substrate highs best explains the sedimentological and glaciotectonic characteristics of the Sunnybrook. The model proposed in this study bears resemblance to earlier glaciolacustrine models described by Eyles and Eyles (1983) and Clark (1986) and refines them by presenting analyses of spatial variability of the Sunnybrook related to variations in substrate topography and depositional water depth (see chapter 4). Controversies regarding the depositional origin of particular features of the Sunnybrook are discussed below, paying particular attention to the characteristics used by Hicock and Dreimanis (1992a, and references therein) to infer subglacial depositional processes. Finally, the Sunnybrook will be compared with the Halton Till, an extensive late Wisconsin subglacial deposit found in southern Ontario that has been interpreted as a lodgement/deformation till (Hibbert, 1990; Boyce and Eyles, 1991).

5.1 FEATURES OF CONTROVERSIAL ORIGIN

Hicock and Dreimanis (1992a) present a strong argument in favour of the Sunnybrook having formed by a combination of subglacial lodgement, subglacial deformation, and glaciolacustrine processes. They suggest that the interbedded contact zone (ICZ) was deposited in a large proglacial lake by processes similar to those presented in this study (**section 4.2**); the ICZ was then overridden by glacier ice as the Laurentide ice sheet (LIS) advanced from the north and east over the whole of the Lake Ontario basin. Overriding by ice of the Scarborough Formation and the ICZ led to both lodgement and deforming bed conditions in subglacial sediments because of the presumed spatial variability in pore water pressures (i.e. high subglacial pore water pressures are necessary for deforming bed conditions; Boulton and Hindmarsh, 1987), and deposited the Sunnybrook diamict. A retreat of the LIS eastward from the Lake Ontario basin re-established a large proglacial lake into which the Sunnybrook's laminated facies were deposited by a succession of fine-grained turbidity currents. Therefore, the model presented by Hicock and Dreimanis (1992a) for deposition of the Sunnybrook differs from the model presented in the present study **only** in the interpretation of depositional environment of the Sunnybrook's diamict facies.

The model of subglacial deforming beds, cited by Hicock and Dreimanis (1992a) as being responsible for deposition of much of the Sunnybrook diamict, is thought to produce great variability in facies and features in the resulting sediments (Alley, 1991; Eyles, N., 1993). Current understanding of deforming bed models suggests that the characteristics presented in **table 5.1** should be sufficient to recognize deformation till facies in the rock and sediment records. Hicock and Dreimanis (1992a) used several of these characteristics to infer subglacial depositional conditions for the Sunnybrook. Subglacial deforming bed conditions were inferred from the presence of parallel and transverse clast and magnetic fabrics, shear planes within the diamict, glaciotectonic "fractures

DIAGNOSTIC CHARACTERISTICS OF DEFORMATION TILLS
· presence of glacitectonized substrates · rafts of substrate incorporated but not completely admixed · "injection" structures from underlying unconsolidated sediments · "augen" structures, indicating differential shearing · inclined shear laminations within massive diamict

Table 5.1 Diagnostic characteristics of deformation tills derived from descriptions of Alley (1991), Boyce and Eyles (1991), Eyles, N. (1993), and Boyce (pers.comm, 1993).

and folds" in the uppermost Scarborough Formation, the incorporation of underlying glaciolacustrine sediments into the lowermost Sunnybrook, and the fracturing of the majority of ostracod valves. Subglacial lodgement conditions were inferred from the presence of parallel striated stone pavements, and discontinuous sharply erosive basal contacts of the Sunnybrook. However, based on the observations made in the present study, the evidence used by Hicock and Dreimanis (1992a) to infer subglacial lodgement or deforming-bed conditions could <u>not</u> be reproduced.

An additional controversial feature important to interpretations of the Sunnybrook environment is the large channels that dissect the upper surface of the Scarborough delta. These have been interpreted as fluvial in origin (Karrow, 1967) and used to infer lowered lake levels (i.e. lake level fluctuations of at least 50 metres) prior to the advance of grounded Sunnybrook ice into the basin. A fluvial interpretation contrasts with ideas proposed in glaciolacustrine interpretations (e.g. Eyles and Eyles, 1983), which argue that lake levels did not change significantly during the whole of early and mid- Wisconsin time. These channels and the "subglacial" characteristics of the Sunnybrook comprise much of the controversy surrounding environmental interpretations of the Sunnybrook. Each will be examined in detail and their depositional origins discussed in the text which follows.

5.1.1 BASAL CLAST HORIZONS

Parallel striated stone pavements (described by Hicock and Dreimanis, 1992a) are equivalent to the basal clast horizons of the present study, and were used as the **primary evidence**, supporting subglacial deposition of the Sunnybrook, by Hicock and Dreimanis (1992a). They report that greater than 50% of clasts are striated within 'pavements' and that both striae and clast a-axes show strong, NE-SW preferred orientations (**Fig. 1.10**). Hicock and Dreimanis (1992a) use these data to suggest that 'striated stone pavements' at the base of the Sunnybrook are the result of subglacial lodgement processes.

The data of the present study do not confirm the results of Hicock and Dreimanis (1992a). Clasts measured in basal clast horizons (in this study) show a weak-to-moderate preferred alignment of clast a-axes at only **one** site (Sylvan Park log 9301; **Fig. 2.9**); the majority of clasts horizons show random clast a-axis orientations, and only a low percentage of clasts are striated ($\approx$10%; **Table 2.2**). The inconsistent (i.e. random) alignment of clast a-axes and lack of striae is not commonly associated with subglacial lodgement processes (Kruger, 1979; Sharp, 1982). Given that the fabric data of Hicock and Dreimanis (1992a) could not be reproduced in the present study, which noted considerable variability in fabric characteristics, a depositional model allowing for spatial variability in the formation of clast horizons is preferred. The model proposed in the present study invokes a subaqueous formation of horizons, possibly as lag surfaces, which in places were overridden by seasonal ice to produce preferred orientations at some but not all sites where clast horizons are presently exposed. Hicock and Dreimanis (1992a) do not explain the spatial variability of 'pavement' occurrence, although they found clast horizons at 4 of their 5 sections along the highs, nor does their subglacial model explain the lack of clast horizons in channels. The restriction of pavements to substrate highs documented in the present study supports a subaqueous origin in which the formation of horizons is dependant upon some maximum lake depth.

5.1.2 DIAMICT AND CONTACT CHARACTERISTICS

In addition to basal clast horizons, Hicock and Dreimanis (1992a) cite three other characteristics of the Sunnybrook diamict to support their subglacial lodgement/deformation till interpretation. These are: parallel and transverse pebble and magnetic fabrics within the diamict, the presence of shear planes, and the nature of the Sunnybrook's basal contact.

Pebble and magnetic fabrics analyzed by Gravenor and Wong (1987) show a weak transverse relationship in the Sunnybrook (i.e. pebble fabric weakly orthogonal to magnetic fabric). This relationship can exist in sediments deformed either by flow or by direct glacial action (Mark, 1974), but it is not commonly observed (Rappol, 1985). These Sunnybrook fabrics were described by Gravenor and Wong (1987) as "incoherent". These fabrics, they concluded, are unlike those found in lodgement tills. and more closely resemble fabrics found in subaquatic debris flows, because clasts are poorly striated and there is a large percentage of low angle and zero-dip clasts. Hicock and Dreimanis (1992a) acknowledge the comments of Gravenor and Wong (1987), yet suggest that subglacial deforming bed models could produce similar fabrics. In their model (Hicock and Dreimanis, 1992a), the deforming bed would "flow away from the zone of release beneath a glacier" (i.e. a subglacial debris flow), and would produce fabrics resembling those of subaqueous debris flows. However, it is noted that this model for fabric development is purely speculative, and no empirical fabric data from known deformation tills are available for comparison.

A second diamict characteristic, used by Hicock and Dreimanis (1992a), to infer subglacial conditions are shear planes, which they found within the Sunnybrook facies, at two stratigraphic positions (within the very lowest and the uppermost portions of the Sunnybrook diamict). In total, shear planes were documented within diamict facies at two of their six sections, and were associated with stratification within the diamict. These shear planes, "commonly coated with silt or sand entrained from underlying sediment" (Hicock and Dreimanis, 1992a), are planar and rise gently in the inferred downglacier direction (to the

SW). In the present study, however, shearing within diamict facies, as described by Hicock and Dreimanis (1992a), was not observed at the Bluffs or along the creeks. Limited shearing, within the lowermost Sunnybrook diamict, was documented within the Guild Inn channel (log 9318; **Fig. 2.1a**). In the context of the proposed glaciolacustrine depositional environment, this isolated shearing is attributed to subaqueous resedimentation processes, which focused materials into channel areas.

The importance of the basal contact of the Sunnybrook diamict with the underlying Scarborough Formation, and its use in palaeoenvironmental interpretations, has been emphasized by Hicock and Dreimanis (1992a) and throughout this thesis. In chapter 2, the Interbedded Contact Zone (ICZ) was described, and interpreted as representing a transitional environment from deltaic Scarborough to deeper water glaciolacustrine conditions. The ICZ is similar to descriptions of a "transitional" contact of Gravenor and Wong (1987, p.2039) and Hicock and Dreimanis (1992a, p.145). However, in areas where the ICZ is absent, the contact may be described as "sharp" (this study), but <u>not</u> as erosional as suggested by Hicock and Dreimanis (1992a). The main arguments against an erosional basal contact are those outlined in chapter 2. Firstly, the contact geometry is planar over the study area (not including the contacts of the CFA). Planar contacts are atypical of subglacially-deposited sediments which are generally excavated into sub-till strata, producing grooves and undulating contacts (Boulton, 1976; Eyles, N. et al., 1982). In the context of "deformation tills", basal incorporation of sub-till sediments (cited as diagnostic criteria; **Table 5.1**), would also lead to non-planar contacts (Boyce and Eyles, 1991). Secondly, it seems unlikely that pervasive shearing of subglacial sediments would be able to preserve the ICZ in <u>most</u> of the High Facies Association, only removing it at isolated sections (e.g. sections 2 and 4 of Hicock and Dreimanis, 1992a; section 9323, this study). Hicock and Dreimanis (1992a) suggest that the absence of the ICZ is an indication of its being 'incorporated' into the lower diamict facies or simply "eroded". However, in the present study, the ICZ was mildly deformed due to imposition of overlying sediments and was not sheared in outcrop locations. It is restricted to highs where winnowing of lake bottom sediments and grounding of seasonal lake ice occurred under shallow lacustrine conditions, as shown in the model proposed in the present study (**Fig. 3.8**).

In summary, the three characteristics of the Sunnybrook diamict used by Hicock and Dreimanis (1992a) to suggest a <u>subglacial</u> depositional environment for the Sunnybrook (e.g. pebble and magnetic fabrics, shear planes, and basal contacts) either cannot be identified in the field or may be interpreted as glaciolacustrine in origin. The present study could not replicate earlier field analyses of shear planes discussed by Hicock and Dreimanis (1992a). In addition, interpretations of subglacial conditions given by Hicock and Dreimanis (1992a), which cause sharp erosive contacts at select locations but allow preservation of easily deformable sediments elsewhere (e.g. ICZ), are inconsistent.

5.1.3 OSTRACODS

The presence of fractured ostracod valves within massive diamict facies was used by Hicock and Dreimanis (1992a) to support an interpretation of subglacial deforming bed conditions for deposition of the Sunnybrook. The degree of preservation of ostracod valves was identified by Westgate et al. (1987), and can be divided into three categories: whole (intact) valves [30%]; valves with minor damage [20%]; and small fragments [50%] (**Fig. 1.7**). The presence of such a large percentage of intact valves within the Sunnybrook has been used to support a glaciolacustrine origin for the Sunnybrook (Westgate et al., 1987; Westgate and Delorme, 1988; Rutka and Eyles, 1989; Schwarcz and Eyles, N., 1991) as such fragile valves are unlikely to have survived subglacial conditions. However, Hicock and Dreimanis (1992a) argue that fragile ostracod valves could be preserved, in a subglacial deforming bed model, citing evidence from other 'fragile' faunas found within tills (foraminfera; Nielson, 1988).

In summary, the presence of ostracods within the Sunnybrook diamict does provide evidence that the sediments were initially deposited in a lacustrine environment. Post- or syn-depositional stresses have caused the fracturing of some of the valves, but have left a significant percentage intact (30%; Westgate et al., 1987). Stresses applied under subglacial conditions are probably **too large** to allow for preservation of intact ostracod valves although there are no empirical data to prove or disprove this theory. In a subaquatic environment, as proposed by the present study, 'rain-out' accumulation and resedimentation of lake bottom sediments seems more likely to have allowed preservation of such a large percentage of the ostracod valves.

5.1.4 DEFORMATION OF SUB-SUNNYBROOK SEDIMENTS

Hicock and Dreimanis (1992a) attribute glacitectonic fractures and folds in the uppermost Scarborough Formation, underlying the Sunnybrook, to subglacial lateral shear stresses. If subglacial conditions are inferred, extensive deformation of sub-till sediments on a regional scale would be expected (c.f. Croot, 1988; Aber, 1993). However, analysis of deformation structures carried out in this study (section 2.3.1; **Figs. 2.24** and **2.25**) shows that the pattern of deformation does not fit a subglacial interpretation.

If the Scarborough Bluffs region had been overridden by grounded glacier ice in early Sunnybrook time, the Scarborough delta itself would have created a large impediment to ice sheet flow (Coleman, 1932). As the upper surface of the Scarborough delta was irregular, **more** subglacial 'stress' would be expected to be applied to the relative highs than to the channels. Thus, two inferences can be made about the characteristics of the uppermost Scarborough Formation sediments: (1) highly erosional contacts should exist on the highs, and (2) more extensive deformation of sub-Sunnybrook sediments should occur on the highs. However, observations made in this study do not confirm these two inferences. In fact, basal contacts, on the highs, are those of the ICZ and are conformable; the deformation of sub-Sunnybrook sediments is more pronounced in the channels and relatively insignificant on the highs (**Fig. 2.23; Table 2.4**). The restriction of much of the sub-Sunnybrook deformation to areas along the margins of the channels suggests that deformation may be associated with the process responsible for channel formation (see section 5.2 below). Limited deformation of the upper Scarborough Formation on the highs is dominated by high angle displacements and was probably due to loading of overburden materials, and not the result of pervasive lateral subglacial shear stresses. Such lateral shear stresses would have had greater impacts both on the soft, readily deformable sediments of the ICZ, and on the underlying Scarborough Formation.

5.2 CHANNELS CUT INTO THE SCARBOROUGH FORMATION

Chapters 3 and 4 emphasize the role of substrate topography in controlling facies types and associations within the Sunnybrook. The upper surface of the underlying Scarborough Formation is extensively channelized and determines whether the Channel Facies Association (CFA) or High Facies Association (HFA) is represented within the Sunnybrook. The origin of these channels, however, has not been resolved and is critical to the reconstruction of early Sunnybrook depositional environments. Three large channels, cut into the Scarborough Formation, were identified along the Bluffs by Karrow (1967): Dutch Church (>50 m deep; ≈ 1.5 km wide), Guild Inn (16 m deep; 1.75 km wide), and Beechgrove (unknown dimensions; see **Fig. 1.2**). Because of their vast dimensions, Karrow (1967) concluded that channels could only have been formed subaerially, dissected by streams flowing to a lowered base level (i.e. lower lake levels). Fluvially-deposited gravels and sands of the Pottery Road Formation, which occupy the base of channels, were used as proof of an interval of fluvial dissection of the Scarborough Delta, prior to the advance of the ice that deposited the Sunnybrook.

In their glaciolacustrine interpretation of the Sunnybrook, Eyles and Eyles (1983) suggested that the channels must have formed subaqueously, as large delta top distributaries in the absence of any evidence within the uppermost Scarborough Formation to confirm subaerial exposure of the delta top (e.g. soil development). In addition, highly variable palaeocurrents, measured within the Pottery Road Formation, were interpreted as characteristic of facies associated with a shifting channel network of a large delta.

Table 5.2 summarizes the various processes that may be responsible for the formation of modern channels in both subaqueous (glaciomarine) and subaerial environments. In fjord settings of British Columbia and Alaska, high amounts of glacially-derived debris are deposited on rapidly aggrading deltas (Kostachuk and McCann, 1987; Phillips and Smith, 1992) that slump to produce turbidity currents, which excavate subaqueous channels. The Guild Inn channel at the Scarborough Bluffs has dimensions comparable to those described from these glaciomarine environments (10-32 m deep; **Table 5.2**) and could have developed by turbidite excavation on a subaqueous delta front. However, the channels at Dutch Church and Beechgrove Drive ($\approx$50 m deep) are probably too large to be

PAPER	CHANNEL DEPTH	CHANNEL WIDTH	CHANNEL LENGTH	PROCESS FORMING CHANNEL
Price, 1973, p.123	30m	400m	4km	· subaerial fluvial dissection: steep channel sides
Kostachuk and McCann, 1987	small chutes	15m	400m	· in deeper waters close to the delta front
Kostachuk and McCann, 1987	20m	180m	<2km	· in shallower waters closer to the inflowing stream
Syvitski and Farrow, 1989	50m	500m	10's of km	· slide (subaqueous) formed "megachannel"
Phillips and Smith, 1992	10-20m	<200m	n/a	· submarine channels maintained by turbidity currents
Kostachuk et al., 1992	32m	>380m	n/a	· turbidity currents, caused by periodic liquefaction of delta mouth sediments
Lagoe et al., 1994	<400m	several km's	n/a	· subaqueous erosion by debris and meltwater from ice margins or the result of large scale downslope failure of rapidly deposited sediment

Table 5.2: Analogues for subaqueous and subaerial formation of large channels, produced by large subaqueous slumps, turbidity currents, or subaerial fluvial dissection.

explained by this process. Other mechanisms of forming large channels are through large subaqueous slides (Syvitski and Farrow, 1989; Lagoe et al., 1994) and subaerial fluvial dissection (Price, 1973; **Table 5.2**); these mechanisms produce channels closest in dimensions to those observed in the Scarborough Formation along the Bluffs, and may be the best interpretations at this time.

The lowered lake level necessary for fluvial dissection of the Scarborough Formation, proposed by Karrow (1967), requires that the ice dam blocking the lake outlet in the St. Lawrence Valley be removed. This suggests a 'retreat' of the ice sheet, which contradicts the gradual cooling trend documented by palynological and paleontological analyses of the Scarborough Formation (Terasmae, 1960; Morgan and Morgan, 1976; Eyles and Williams, 1992), towards cooler, more glacial conditions with an inferred expansion of the ice sheets towards the top of the formation. Thus, it seems unlikely that lake levels lowered dramatically or the channels formed by subaerial fluvial dissection. In addition, there is no evidence to suggest subaerial exposure (e.g. soil development) at the top of the Scarborough Formation.

The large channel at the Dutch Church section does show remarkable similarities to megachannels described by Lagoe et al. (1994) in glaciomarine deposits of Alaska (**Table 5.2**). These glaciomarine megachannels are thought to have formed by downslope slumping of large masses of rapidly deposited sediment and a similar origin may be suggested for the Scarborough Formation channels. Growth faulting and failure of delta front sediments are widely reported in both modern (Kostachuk and McCann, 1987; Phillips et al., 1991;) and ancient (Bhattacharya and Walker, 1992) deltaic settings. The large channels on the upper surface of the Scarborough Formation may therefore represent slump-generated megachannels for two reasons. Firstly, the upper facies of the Scarborough Formation within channels show a moderate amount of faulting-type deformation which is absent from the relative highs. Secondly, instability of both delta front and 'channel wall' sediments during the early Wisconsin is reflected by facies deposited by resedimentation processes contained within the immediately overlying Sunnybrook diamict.

5.3 COMPARISON OF SUNNYBROOK AND HALTON DIAMICTS

Hicock and Dreimanis (1992a) raise some interesting questions when they suggest that the Sunnybrook may be interpreted in part as a deformation till. Section 5.1 above demonstrates that all of the features they attribute to subglacial depositional conditions can be reinterpreted as glaciolacustrine or else cannot be replicated (e.g. preferential alignment of clast a-axes in basal clast horizons). In order to further demonstrate the inadequacy of a subglacial depositional model to account for the Sunnybrook diamict, the Sunnybrook will be compared with an undisputed subglacial deposit, the Halton Till (Randall and Boyce, 1993).

The recognition of deformation till in ancient sediments relies upon the identification of several diagnostic facies characteristics (**Table 5.1**). In the Scarborough area, Hibbert (1990), Boyce and Eyles (1991) and J. Boyce (pers.comm., 1993) have recently re-interpreted portions of the late Wisconsin Halton till as deformation till. The main evidence, in support of deforming bed conditions during Halton time, is the presence of undulating and erosive basal contacts, and rafts of sub-till sediments within lower Halton facies. Hibbert (1990) demonstrated how the matrix texture of the Halton till is related to the texture of underlying sediments. The Halton till's matrix has a high percentage of fines in areas where it overlies silt and clay facies, and a high percentage of sand where it overlies sand facies (**Fig. 5.1**). Complete admixing of these substrate sediments influences the textural character of the lower Halton and suggests that the Halton has "pirated" sediments from underlying formations.

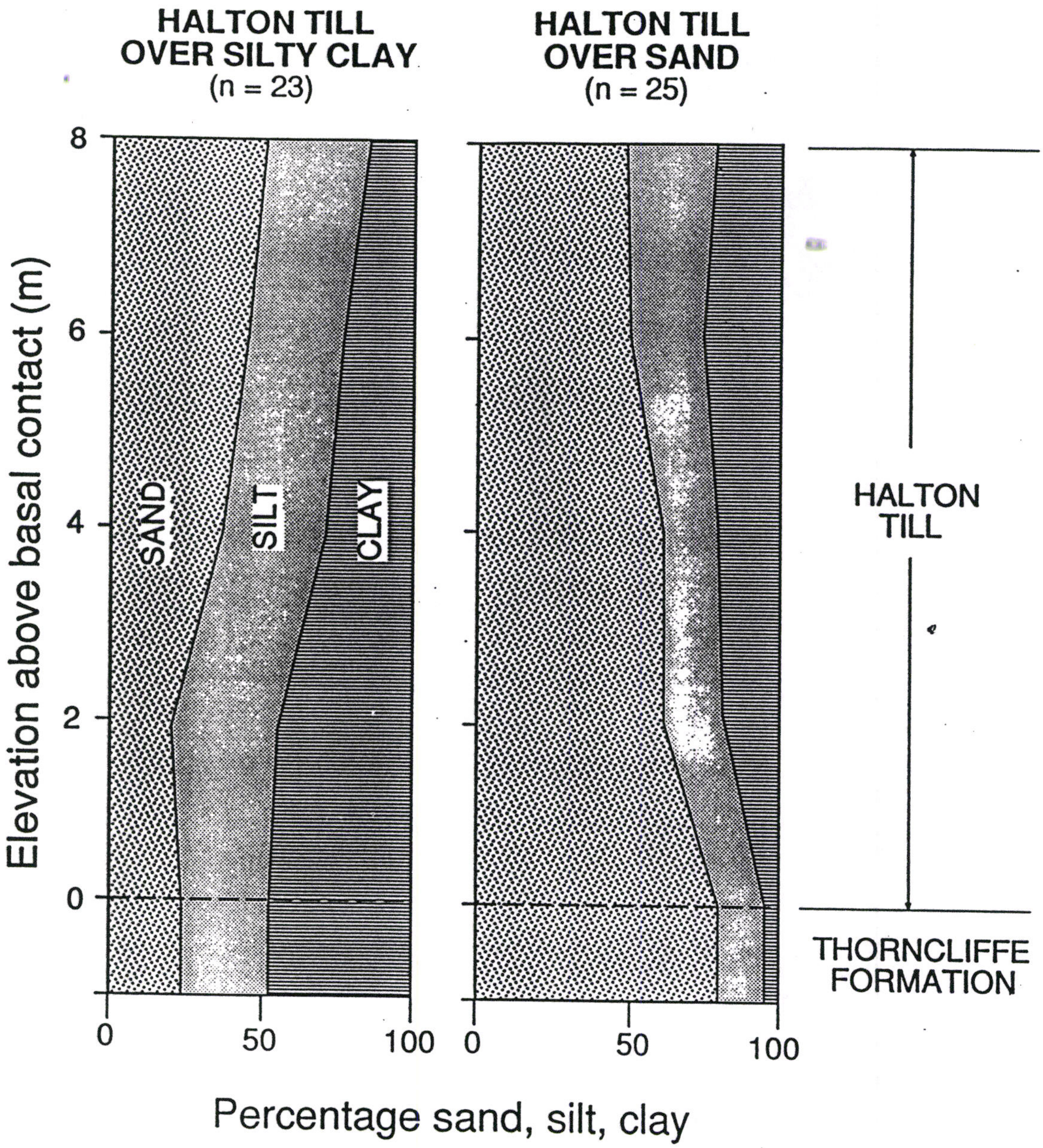


Figure 5.1: Matrix texture analyses of the Halton "deformation" till. Textural character of the matrix is intimitely related to the underlying sediments. The deformation till model hypothesizes the incorporation of sub-till materials. Data are those compiled by Hibbert (1990).

Overall, the Halton Till matrix is coarser-grained with many more large clasts and bullet shaped boulders than the Sunnybrook which is very fine-grained and closely resembles lacustrine mud. In addition, non-planar and undulating basal contacts of the Halton, showing several metres of relief, have been observed in outcrops along Rouge and Duffins Valleys by the author and J.Boyce (e.g. Rouge sections 9307A,B, 9309; **Figs. 2.1b** and **2.32**). Above these contacts, rafts of underlying mid-Wisconsin Thorncliffe sands and Sunnybrook diamict are identified within the Halton facies (Boyce, pers.comm., 1993).

Facies and basal contacts of the Sunnybrook are not at all similar to those of the Halton Till and do not suggest an origin by subglacial deformation for several reasons (Randall and Boyce, 1993). Firstly, basal contacts of the Sunnybrook are predominantly planar and horizontal, in areas away from channels (**Figs. 2.28** and **2.29**), not as undulating and erosive as those of the Halton. Secondly, there is no evidence, within the lowermost Sunnybrook, to suggest basal incorporation and rafting of the underlying Scarborough Formation. Evidence of incorporation or rafting of substrata would include the presence of "injection" and "augen" structures and sheared sediments throughout diamict facies (**Table 5.1**). None of these rafting 'indicators' were observed within any of the Sunnybrook facies but are present within the Halton Till (Boyce, pers. comm., 1993; Randall and Boyce, 1993).

5.4 CONCLUSION

The preceding discussion has reviewed the controversial issues surrounding current interpretations of the Sunnybrook diamict's depositional environment. From what is known of subglacial lodgement and deformation till processes, and their associated facies and contacts, the facies and contacts of the Sunnybrook diamict could not have been formed in a subglacial position. Comparisons made to deformation till facies of the late Wisconsin Halton Till also refute a subglacial interpretation for the Sunnybrook. Rather, evidence in support of glaciolacustrine processes for formation of the Sunnybrook diamict, is prevalent in outcrops at both the Scarborough Bluffs and along the Rouge and Duffins Valleys. Most importantly, the context of Sunnybrook diamict facies needs to be stressed. The Sunnybrook diamict shows conformable contacts (both upper and lower) with two **known** lacustrine facies (see chapter 2) -- laminated Sunnybrook and ICZ Sunnybrook -- and contains structures that can only be presently attributed to subaquatic environments (e.g. intact clay beds and fine silt stringers within massive diamict facies). It is these facies characteristics and relationships of the diamict, with over- and underlying lacustrine facies, that most strongly support a glaciolacustrine origin for the whole of the Sunnybrook.

CHAPTER 6: CONCLUSIONS

The main objective of this study was to complete a regional sedimentological analysis of the Sunnybrook and related formations, in order to establish a model summarizing the Sunnybrook's depositional origin. In light of the controversy concerning the origin of the Sunnybrook as either glaciolacustrine (Eyles and Eyles, 1983) or subglacial (Karrow, 1967; Hicock and Dreimanis, 1992a), the present study aimed to determine sedimentological criteria on which to base paleoenvironment interpretation. Facies, contacts, and structural characteristics of the Sunnybrook were compared to similar features in both subglacial and subaqueous environments. The following list summarizes the methodology and main findings of the study.

(1) Sedimentological investigation of the Sunnybrook identified massive and stratified diamict facies which, in places, contain clast horizons and interbedded sands and muds in the basal contact zone, and identified both undisturbed and deformed fine-grained laminated facies. Diamict facies closely resemble those produced by subaqueous rain-out and resedimentation processes. Units of undisturbed clay laminae preserved **within** massive diamicts suggest intermittent 'quiet' conditions during deposition of the Sunnybrook diamict. In addition, contacts of the Sunnybrook with the underlying Scarborough Formation and overlying Thorncliffe Formation suggest the continuous presence of a large

proglacial lake in the Ontario basin during deposition of the Sunnybrook and related formations (see point **5** below).

(2) Two distinct facies associations are defined in a depositional model proposed for the Sunnybrook, the Channel (CFA) and High Facies Associations (HFA). The CFA is identified by its position within topographic lows in the underlying strata formed either by channels cut into the top of the Scarborough Formation, as seen along the Bluffs, or by bedrock channels present in the dissecting creeks. Characteristic facies of the CFA are thick units of massive and stratified diamict (10-18 m thick) overlain by successions of finely-bedded turbidites (e.g. laminated facies). Diamict facies of the CFA contain sedimentological features suggesting subaqueous resedimentation such as silt clast breccia horizons and flow noses and are interpreted predominantly as debris flow facies. Limited deformation of upper Scarborough Formation sediments underlying the CFA suggests that deformation may be related to the process which formed the channels (see point **3.2** below). The upper contact of the CFA with overlying sands is gradational, recorded as the upsection coarsening of turbidites caused by the advance of the Thorncliffe delta into the basin.

The HFA is readily identified along the Bluffs by its position away from topographic lows. The HFA comprises a comparatively thin unit of massive and stratified diamict facies (5-7 m thick) which has planar and predominantly interbedded basal contacts (ICZ) with the underlying Scarborough Formation. Diamict accumulated primarily as a result of 'rain-out' of suspended fines and ice-rafted debris. Several features of the Sunnybrook are found **exclusively** within the HFA and include the ICZ, basal clast horizons, and a loaded upper contact. The ICZ records a gradual deepening of the lake at the beginning of the Sunnybrook interval, and basal clast horizons suggest grounding of seasonal lake ice on the highs (see point **3.3** below).

(3) A depositional model is proposed for the Sunnybrook which confirms a glaciolacustrine depositional environment. The main implications of this model are summarized below.

(3.1) The formation of a large lake in the Lake Ontario basin during deposition of the Sunnybrook requires that an ice dam blocked the basin's normal drainage outlet in the St. Lawrence Valley. Thus, the position of the ice margin during Sunnybrook time was located a distance north and east of Scarborough, although the exact location cannot be determined because of the absence of ice-proximal facies.

(3.2) Sub-Sunnybrook deformation within the upper Scarborough Formation is concentrated in channels and thus may have been caused by the process which formed the channels. Channels are believed to have formed immediately prior to Sunnybrook deposition either as large subaqueous slumps or as part of a distributary channel network which existed on top of the Scarborough Delta.

(3.3) Topography of the substrate was identified as a major control on facies variability within the glaciolacustrine environments of the proposed model **(Fig. 3.8)**. The **shallow** glaciolacustrine environments which existed on the

topographic highs (HFA) during early Sunnybrook time allowed winnowing and traction current activity to produce the ICZ and clast lags within the accumulating diamict. Clast lags were in places abraded by grounding seasonal lake ice. **Deeper** glaciolacustrine conditions existed in topographic lows and precluded the development of either the ICZ or basal clast horizons within the CFA. Accumulating diamict facies on channel walls within the CFA were unstable and resedimented into substrate lows resulting in thicker diamict units in the CFA.
(3.4) As the Sunnybrook ice margin withdrew from the basin, delta progradation in the Scarborough region produced a sediment source for turbidity currents and density underflows. These processes deposited the laminated facies of the CFA in the remaining topographic lows on the lake floor. The lessening influence of ice in the Ontario basin at this time is reflected by the cessation of diamict accumulation and by the disappearance of ice-rafted debris moving upsection through the fine-grained laminated facies. Within the CFA, the gradual upward coarsening of the succession of turbidites reflects advance of the Thorncliffe delta and may indicate reducing water levels. In the HFA, a loaded upper contact marked by sand pillows of the Thorncliffe Formation is evidence that the delta advanced rapidly over the diamict facies of the HFA.

(4) The proposed glaciolacustrine model of deposition for the Sunnybrook provides a re-interpretation of facies, basal clast horizons and sub-Sunnybrook deformation previously attributed to subglacial processes by Hicock and Dreimanis (1992a). Massive and stratified diamict facies and unit geometries were shown to have more similarities to subaqueous rain-out and resedimentation processes than to subglacial deformation or lodgement processes. A new model to explain the spatial and stratigraphic position of basal clast horizons is proposed which suggests that shallow glaciolacustrine conditions in early Sunnybrook time were critical, allowing the winnowing of lake bottom sediments and isolated grounding of seasonal lake ice.

(5) The glaciolacustrine model for deposition of the Sunnybrook proposed in this study supports the contentions of Schwarcz and Eyles (1991, and references therein) that glaciolacustrine conditions prevailed in the Lake Ontario basin for the early to mid-Wisconsin at the Scarborough Bluffs; each of the Scarborough, Sunnybrook, Seminary, Meadowcliffe and Thorncliffe Formations were deposited in this high level lake. Only in late Wisconsin time did the Laurentide Ice Sheet (LIS) advance over the Lake Ontario basin and cover the entire glaciolacustrine succession with the Halton Till. Therefore, the stratigraphic significance of the proposed model is twofold. Firstly, if continuous glaciolacustrine conditions are inferred for the Ontario basin from early until late Wisconsin, the division of the Scarborough sequence with "formational boundaries" is artificial. Boundaries should be based on major changes in environmental conditions and not simply on lithological differences between units. Secondly, the identification of glaciolacustrine conditions along the southern margin of the LIS in the Lake Ontario basin may be significant for the interpretation and correlation of glacigenic sequences in other Great Lake basins. Glaciolacustrine deposits and

successions are basin-specific and individual lithological units cannot be correlated from basin to basin in order to identify major ice-marginal shifts as has been done in the past (Karrow, 1967, 1984b; Dreimanis, 1977). Elsewhere, within the Lake Ontario basin, correlations of glacigenic successions, using the sedimentological descriptions and structural characteristics identified within the Sunnybrook, would be useful to test the broader implications of the depositional model. Specifically, exposures at the Bowmanville Bluffs, 50 km east of Scarborough, which are described by Brookfield et al. (1982) as "close cousins" to the Scarborough sequence, would be good candidates for correlation and/or model testing.

(6) There are two questions raised by this and other studies which may stimulate future research on the Sunnybrook. Firstly, the Sunnybrook diamict matrix has a high degree of textural variability which has not been adequately examined (Karrow, 1967; Eyles, 1982; this study). Some of the data collected suggests that the diamict matrix texture may be coarser-grained in the CFA than in the HFA. Additional sampling of Sunnybrook diamict matrix **may** confirm ideas about the deposition of coarser-grained sediments in subaqueous channels in a glaciolacustrine setting, analogous to subaqueous glaciomarine channels on rapidly aggrading delta fronts (Carlson et al., 1992; Kostachuk et al., 1992). Secondly, the data collected from basal clast horizons in this study are used to provide a new interpretation of poorly striated, planar, discontinuous clast horizons. However, there are discrepancies between clast fabric data collected for basal clast horizons in this study and previous studies (Hicock and Dreimanis, 1989, 1992a), particularly with regards to the frequency of striated clasts and the fabric strength of the preferred major axis orientations (**Figs. 1.10** and **2.9**). Additional data collection may help to resolve debate over the Sunnybrook's clast horizons and to advance the debate in the literature over the model of formation of clast horizons and clast pavements in subaqueous versus subglacial environments (Clark, 1991; Mickelson et al., 1992; Eyles, C.H., 1994).

In summary, the Sunnybrook is part of the early and mid-Wisconsin glaciolacustrine succession exposed at Scarborough Bluffs. This succession includes the Sunnybrook, Seminary, and Meadowcliffe units, and the three members of the Thorncliffe Formation, and argues for the continuous presence of an extensive lake which was dammed by ice in the St. Lawrence Valley. The diamicts were deposited during periods when active iceberg calving into a large proglacial lake was occurring along an extensive ice margin. Periodic retreat of the ice sheet led to the re-establishment of a terrestrial drainage network north and east of the Bluffs, and deposition of extensive deltaic sands (Thorncliffe Formation) over the underlying glaciolacustrine diamicts.

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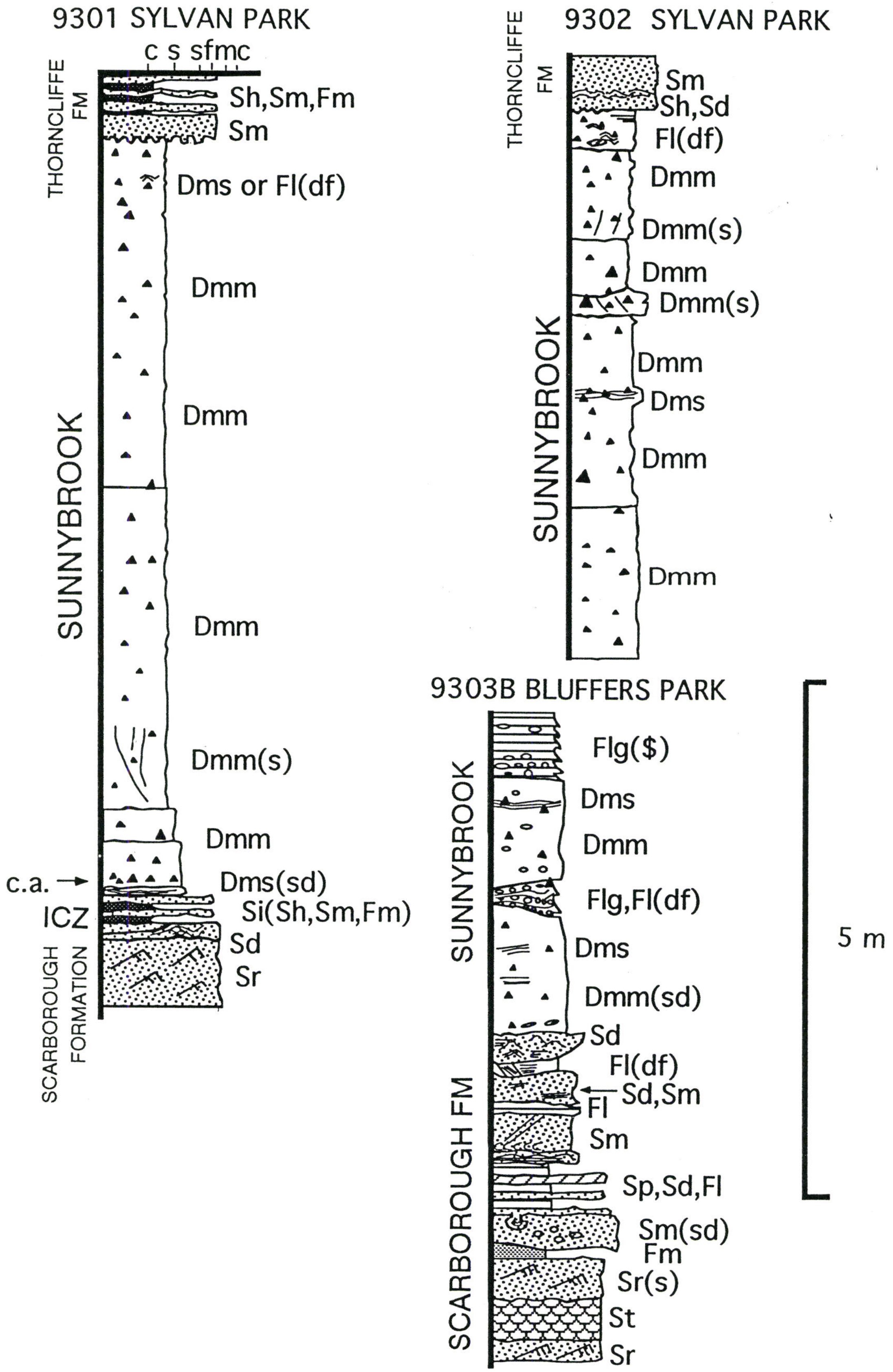
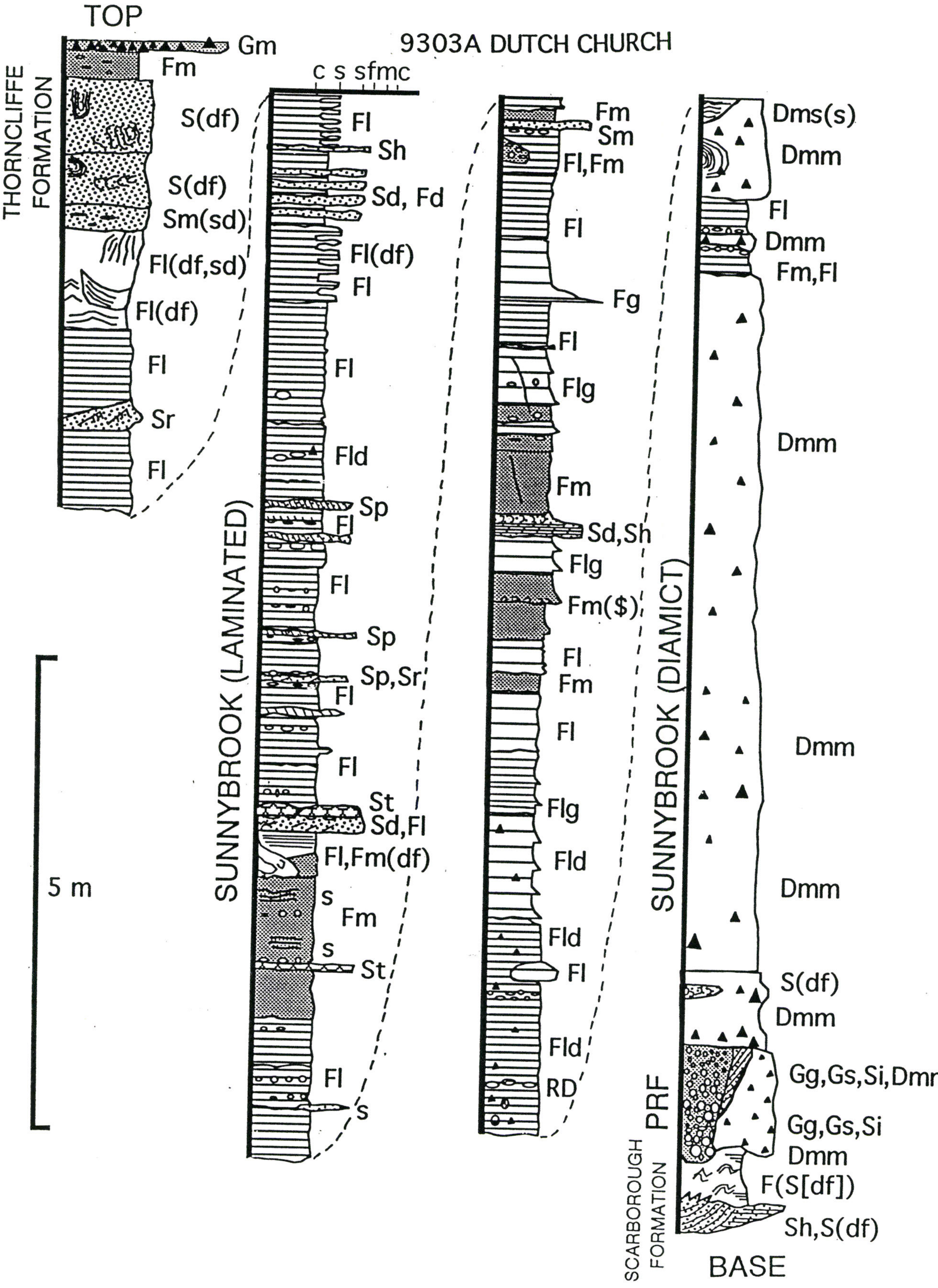
APPENDIX A:

SEDIMENT LOGS

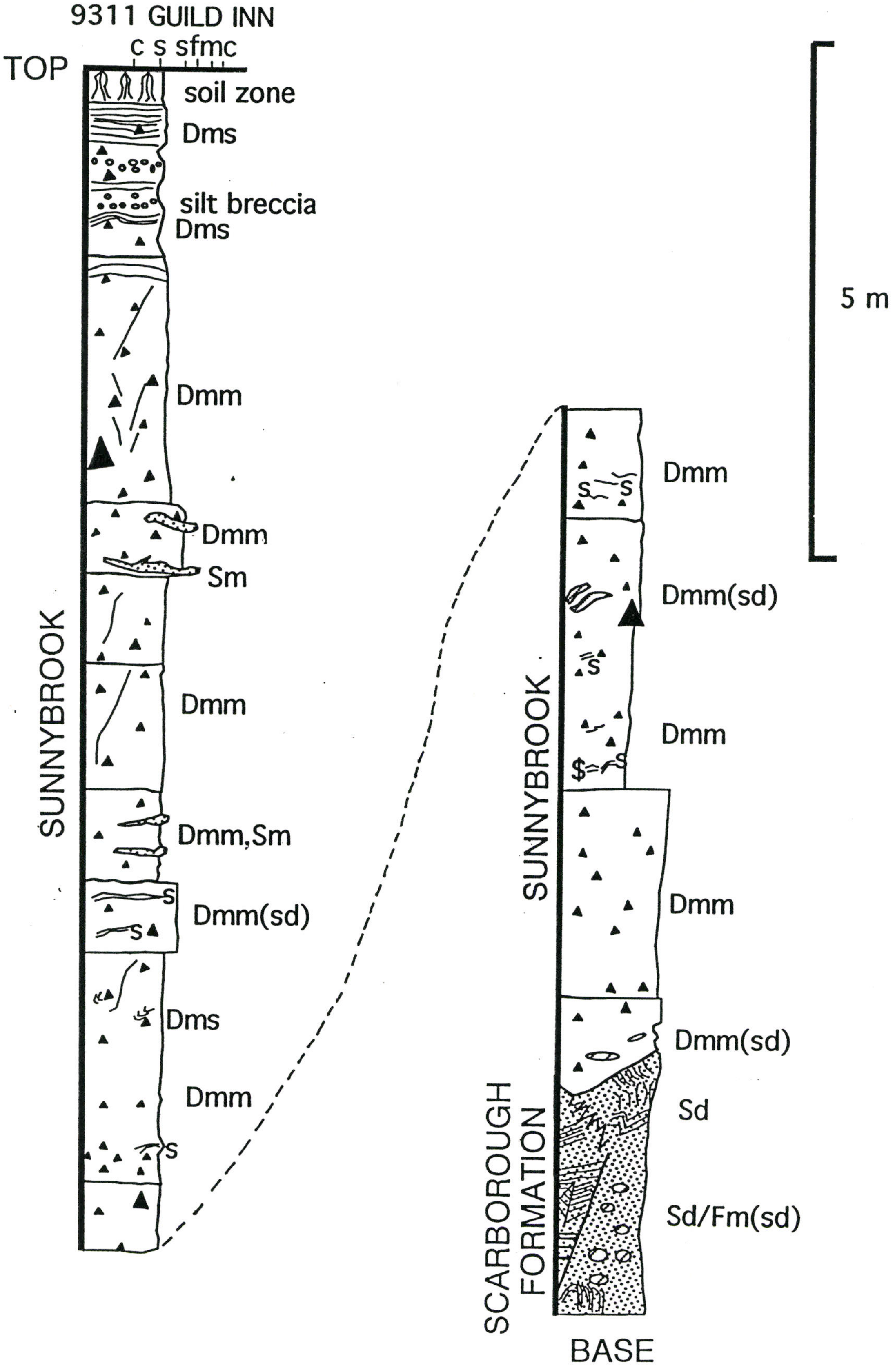
Refer to Figure 1.11 for the description of the lithofacies codes.

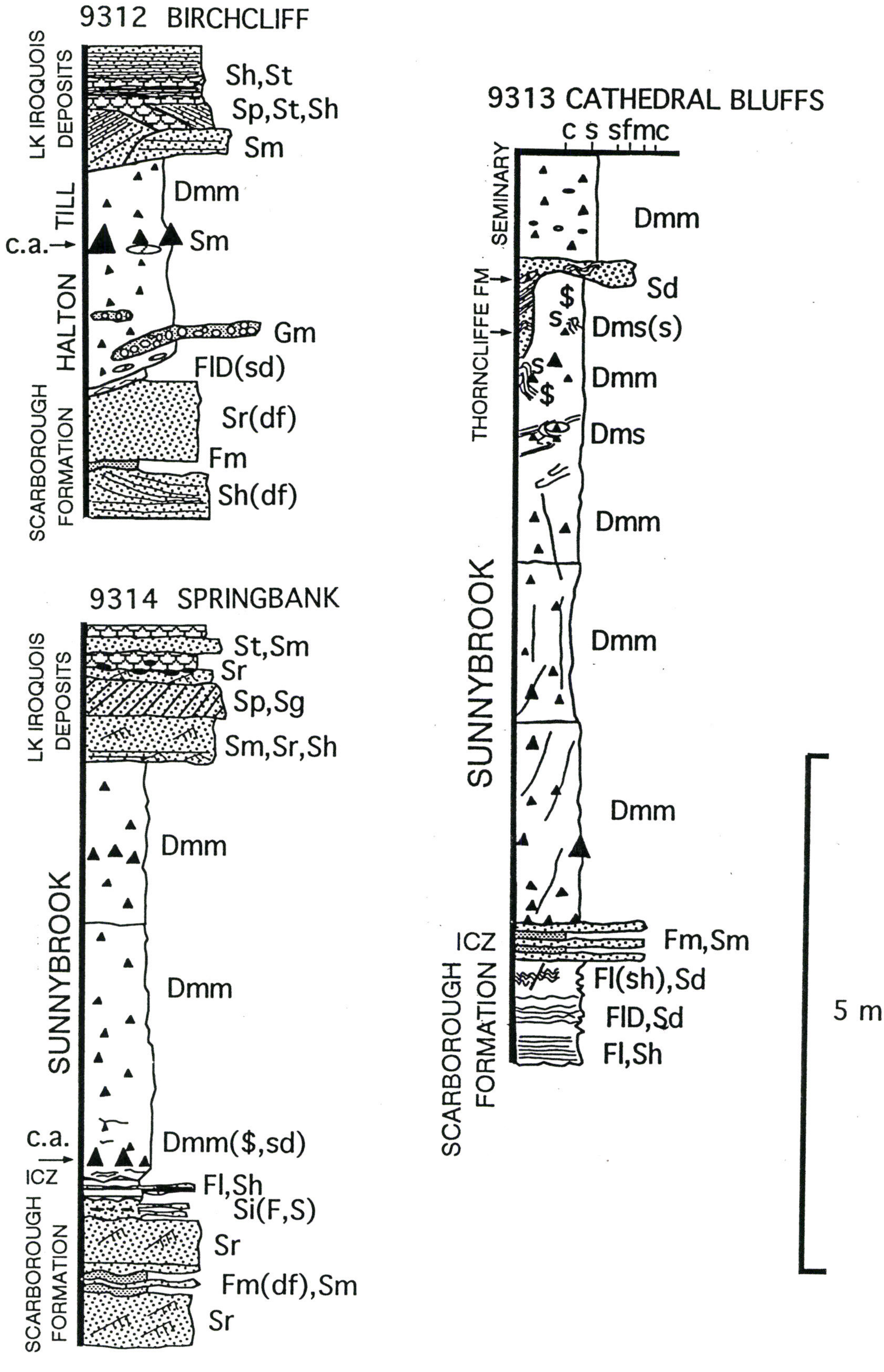


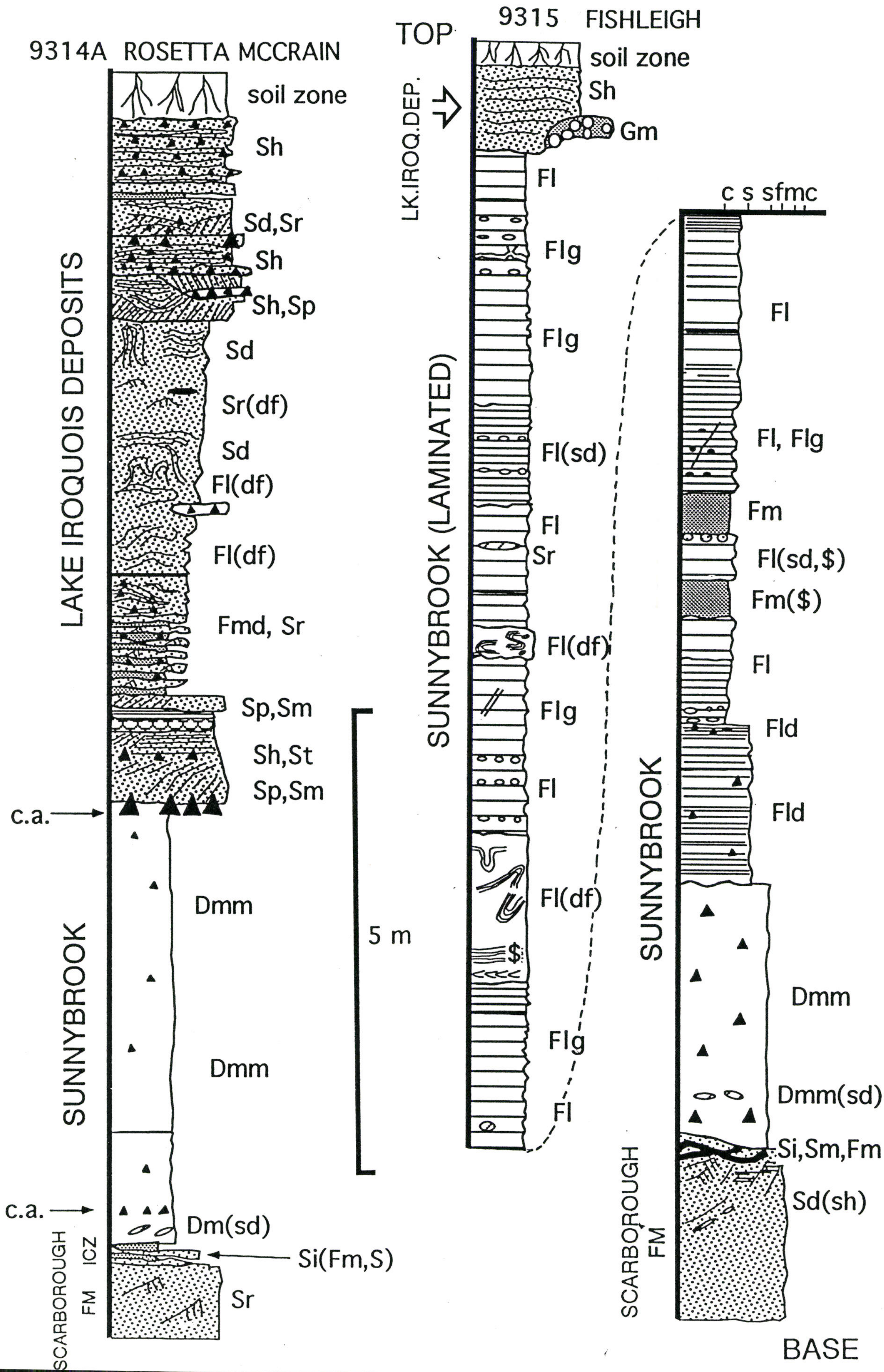
9301 SYLVAN PARK
c s sfmc
THORNCLIFFE FM
Sh,Sm,Fm
Sm
Dms or Fl(df)
Dmm
Dmm
SUNNYBROOK
Dmm
Dmm(s)
Dmm
c.a.
Dms(sd)
ICZ
Si(Sh,Sm,Fm)
Sd
Sr
SCARBOROUGH FORMATION
9302 SYLVAN PARK
THORNCLIFFE FM
Sm
Sh,Sd
Fl(df)
Dmm
Dmm(s)
Dmm
Dmm(s)
Dmm
Dms
Dmm
SUNNYBROOK
Dmm
9303B BLUFFERS PARK
SUNNYBROOK
Flg($)
Dms
Dmm
Flg,Fl(df)
Dms
Dmm(sd)
Sd
Fl(df)
Sd,Sm
Fl
Sm
Sp,Sd,Fl
Sm(sd)
Fm
Sr(s)
St
Sr
SCARBOROUGH FM
5 m



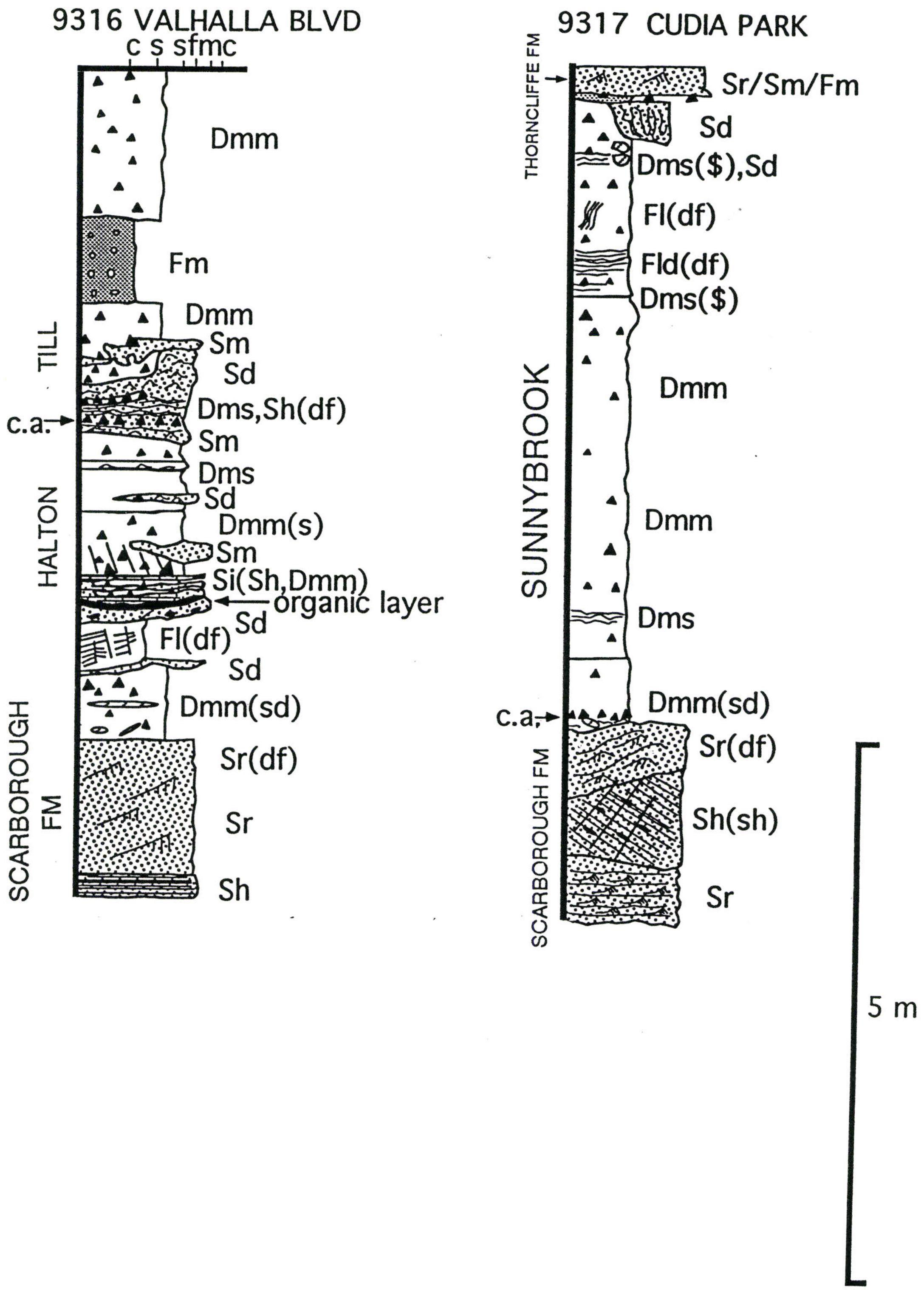
TOP
9303A DUTCH CHURCH
THORNCLIFFE FORMATION
Gm
Fm
S(df)
S(df)
Sm(sd)
Fl(df,sd)
Fl(df)
Fl
Sr
Fl
c s sfmc
Fl
Sh
Sd, Fd
Fl(df)
Fl
Fl
Fld
Sp
Fl
Fl
Sp
Sp,Sr
Fl
Fl
St
Sd,Fl
Fl,Fm(df)
s
Fm
s
St
Fl
s
SUNNYBROOK (LAMINATED)
Fm
Sm
Fl,Fm
Fl
Fg
Fl
Flg
Fm
Sd,Sh
Flg
Fm($)
Fl
Fm
Fl
Flg
Fld
Fld
Fl
Fld
RD
SUNNYBROOK (DIAMICT)
Dms(s)
Dmm
Fl
Dmm
Fm,Fl
Dmm
Dmm
Dmm
S(df)
Dmm
Gg,Gs,Si,Dmm
Gg,Gs,Si
Dmm
F(S[df])
Sh,S(df)
PRF
SCARBOROUGH FORMATION
BASE
5 m


9311 GUILD INN
c s sfmc
TOP
soil zone
Dms
silt breccia
Dms
Dmm
Dmm
Sm
Dmm
Dmm,Sm
Dmm(sd)
Dms
Dmm
SUNNYBROOK
5 m
Dmm
Dmm(sd)
Dmm
Dmm
Dmm(sd)
Sd
Sd/Fm(sd)
SUNNYBROOK
SCARBOROUGH FORMATION
BASE

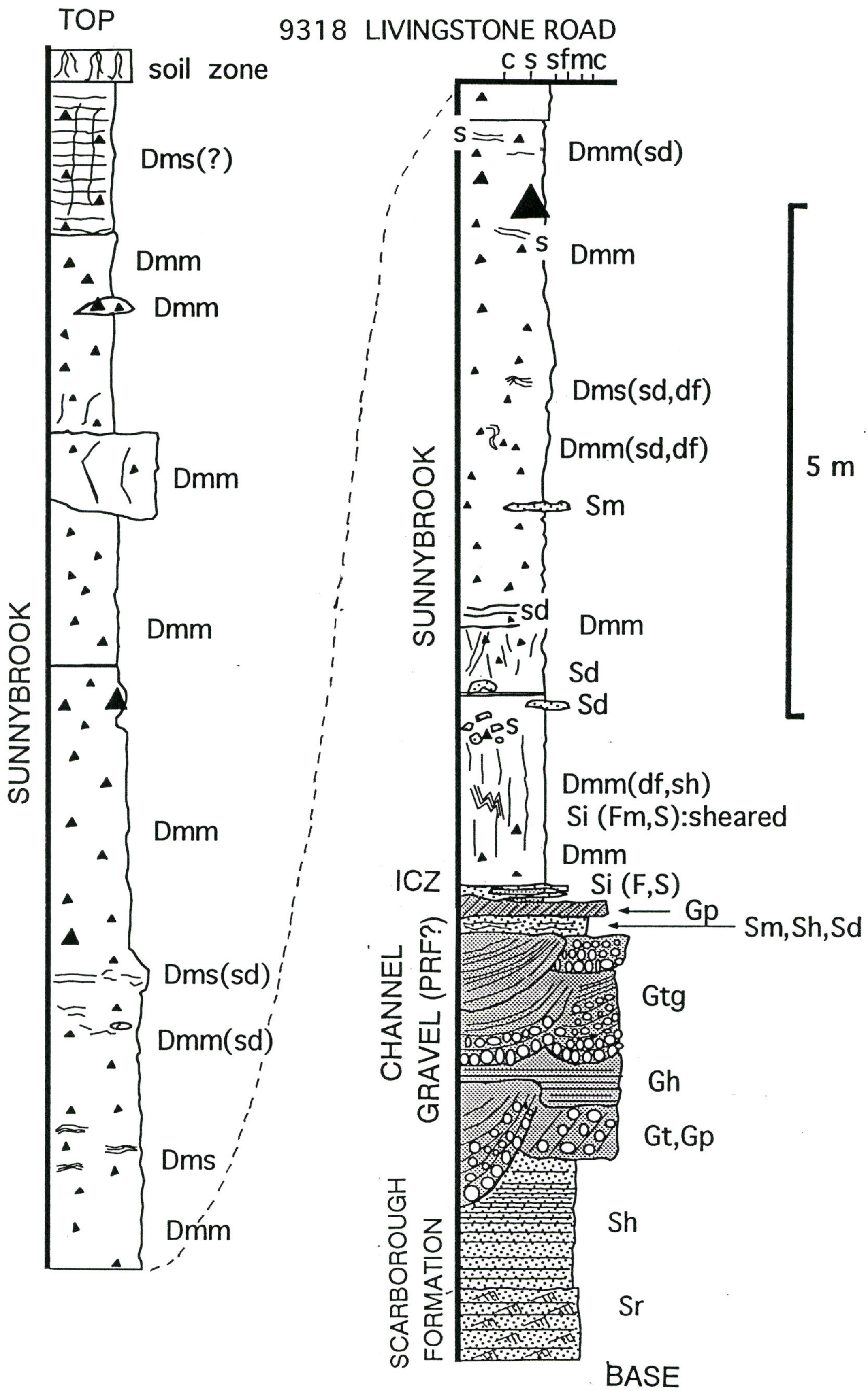

9312 BIRCHCLIFF
LK IROQUOIS DEPOSITS
Sh,St
Sp,St,Sh
Sm
TILL
Dmm
c.a.
Sm
HALTON
Gm
FlD(sd)
SCARBOROUGH FORMATION
Sr(df)
Fm
Sh(df)
9314 SPRINGBANK
LK IROQUOIS DEPOSITS
St,Sm
Sr
Sp,Sg
Sm,Sr,Sh
SUNNYBROOK
Dmm
Dmm
c.a.
Dmm($,sd)
ICZ
Fl,Sh
Si(F,S)
SCARBOROUGH FORMATION
Sr
Fm(df),Sm
Sr
9313 CATHEDRAL BLUFFS
c s sfmc
SEMINARY
Dmm
THORNCLIFFE FM
Sd
Dms(s)
Dmm
Dms
SUNNYBROOK
Dmm
Dmm
Dmm
ICZ
Fm,Sm
SCARBOROUGH FORMATION
Fl(sh),Sd
FlD,Sd
Fl,Sh
5 m



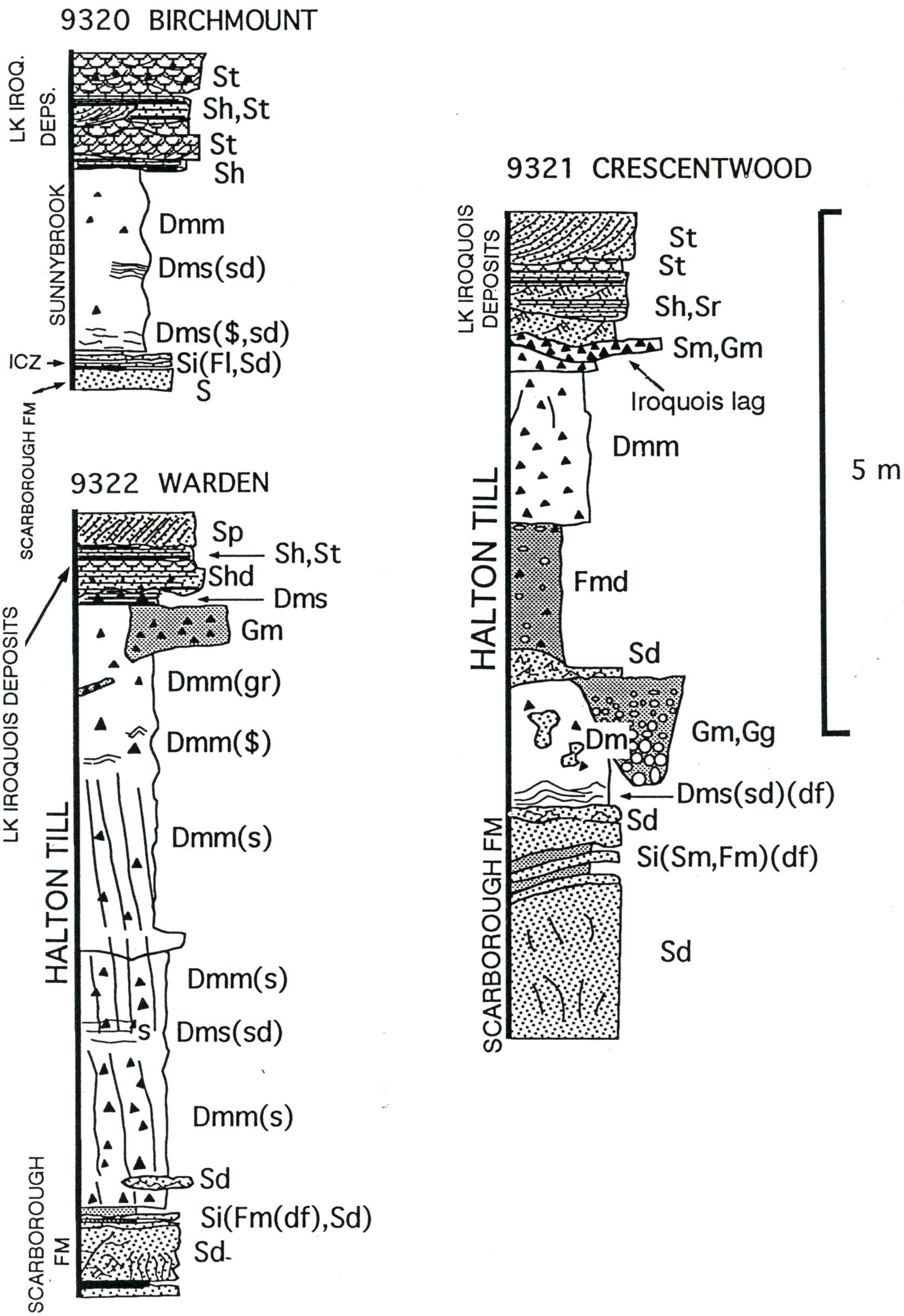
9314A ROSETTA MCCRAIN
soil zone
Sh
Sd,Sr
Sh
Sh,Sp
Sd
Sr(df)
Sd
Fl(df)
Fl(df)
Fmd, Sr
Sp,Sm
Sh,St
Sp,Sm
LAKE IROQUOIS DEPOSITS
c.a.
Dmm
Dmm
SUNNYBROOK
c.a.
Dm(sd)
Si(Fm,S)
Sr
SCARBOROUGH FM
ICZ
5 m
TOP
9315 FISHLEIGH
LK.IROQ.DEP.
soil zone
Sh
Gm
Fl
Flg
Flg
Fl(sd)
Fl
Sr
Fl(df)
Flg
Fl
Fl(df)
Flg
Fl
SUNNYBROOK (LAMINATED)
c s sfmc
Fl
Fl, Flg
Fm
Fl(sd,$)
Fm($)
Fl
Fld
Fld
Dmm
Dmm(sd)
Si,Sm,Fm
Sd(sh)
SUNNYBROOK
SCARBOROUGH FM
BASE

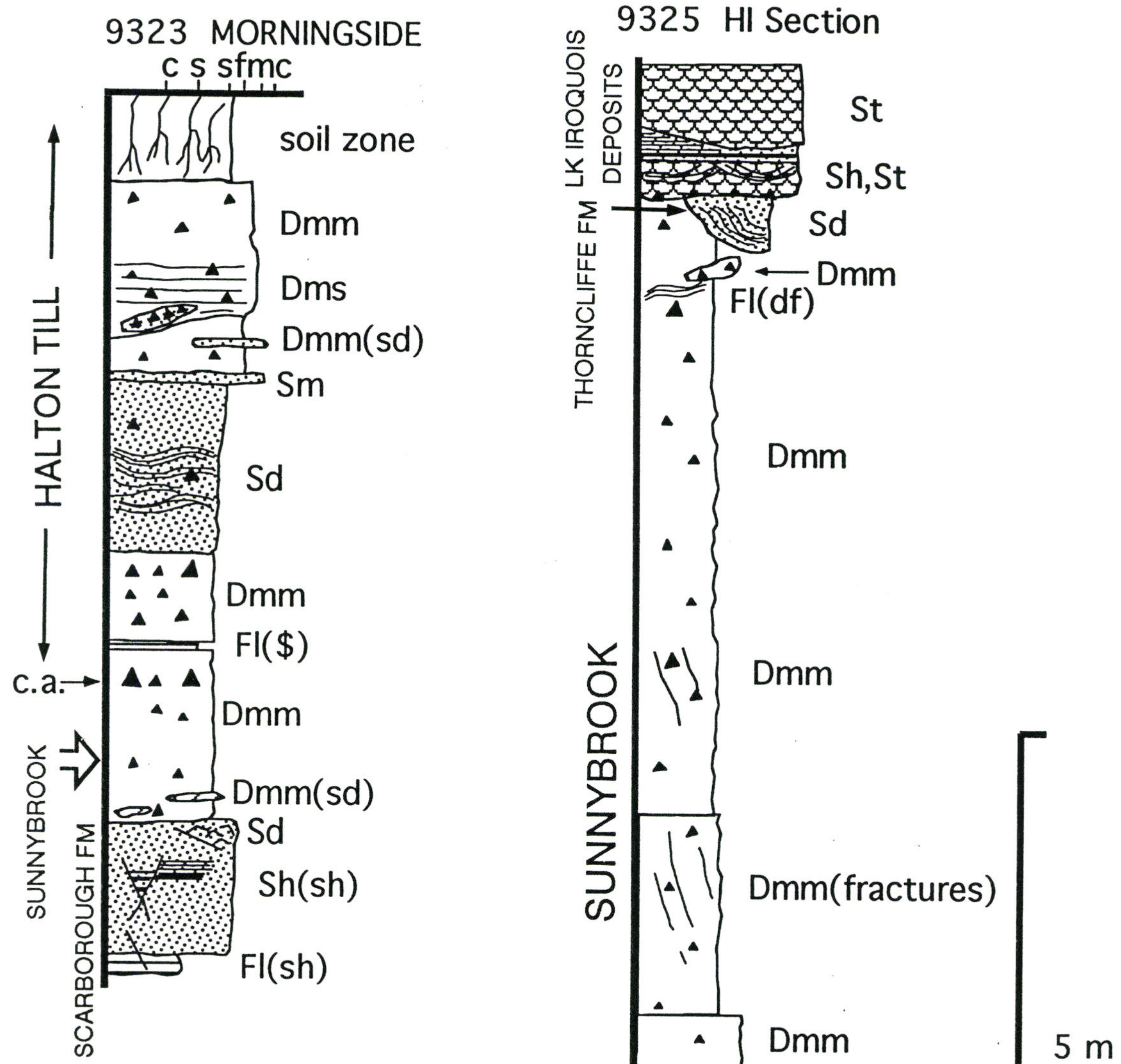


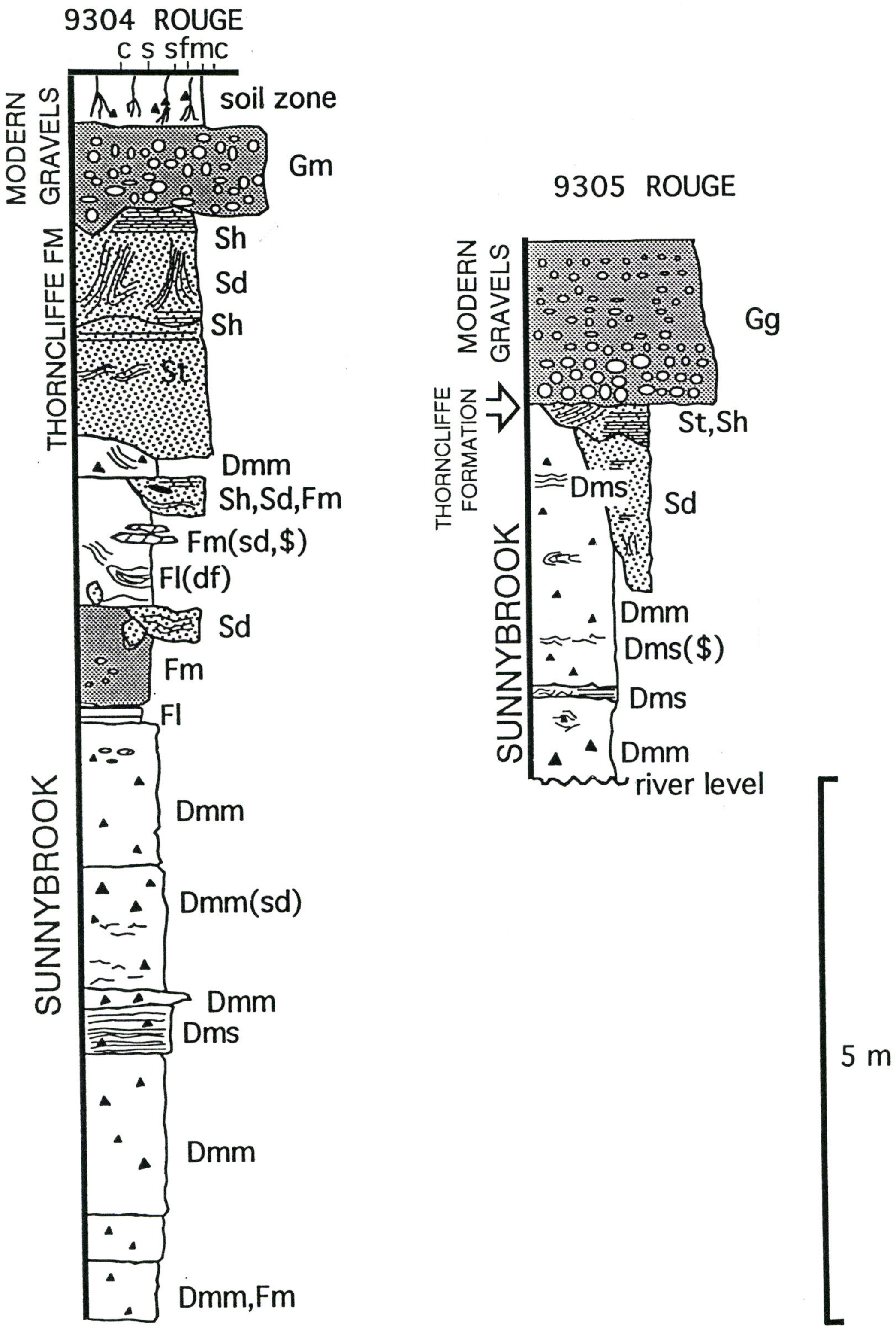
9316 VALHALLA BLVD
c s sfmc
Dmm
Fm
Dmm
Sm
Sd
Dms,Sh(df)
c.a.
Sm
Dms
Sd
Dmm(s)
Sm
Si(Sh,Dmm)
organic layer
Sd
Fl(df)
Sd
Dmm(sd)
Sr(df)
Sr
Sh
TILL
HALTON
SCARBOROUGH FM
9317 CUDIA PARK
THORNCLIFFE FM
Sr/Sm/Fm
Sd
Dms($),Sd
Fl(df)
Fld(df)
Dms($)
Dmm
Dmm
Dms
Dmm(sd)
c.a.
Sr(df)
Sh(sh)
Sr
SUNNYBROOK
SCARBOROUGH FM
5 m



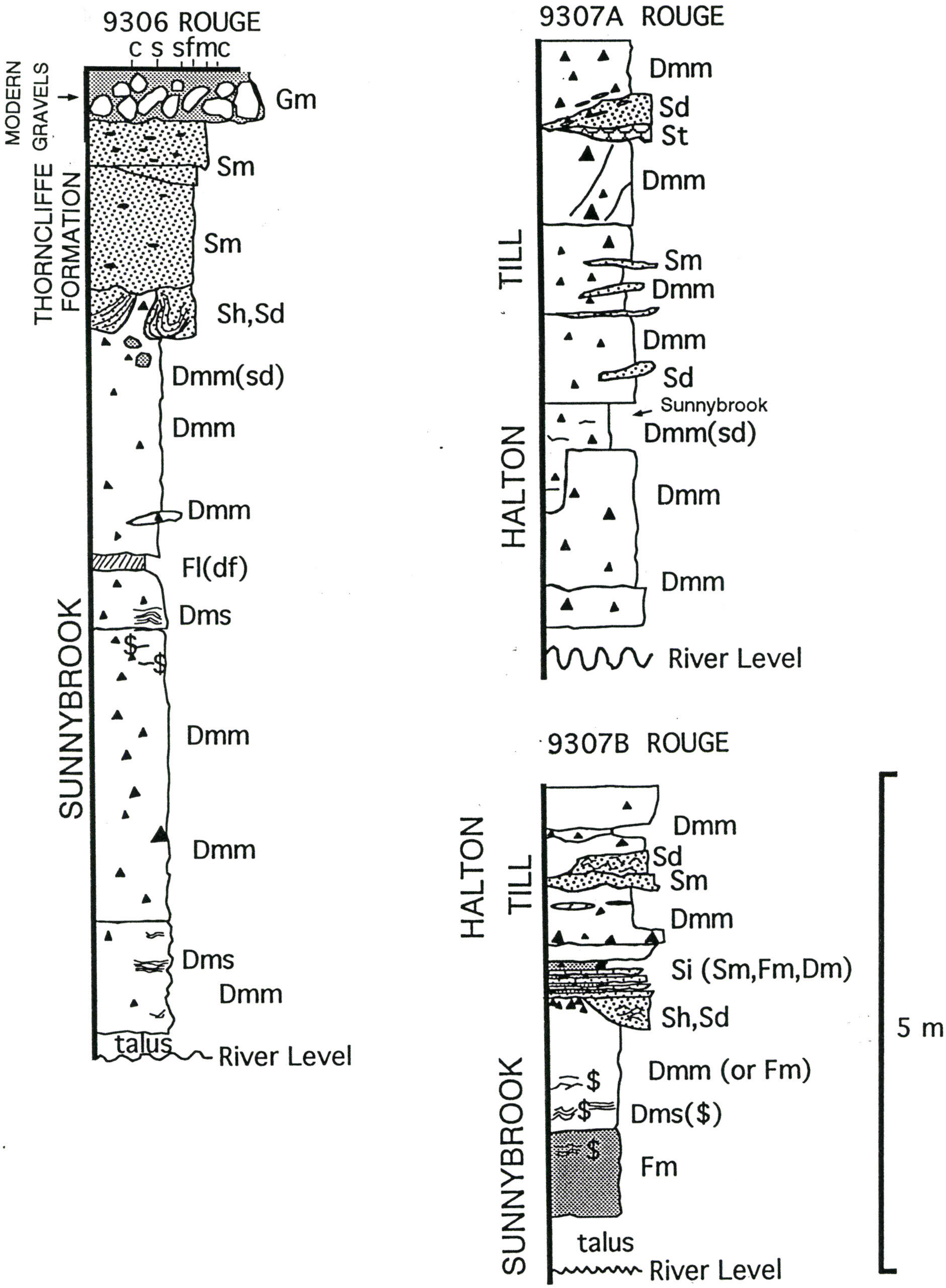
TOP
9318 LIVINGSTONE ROAD
c s sfmc
soil zone
Dms(?)
Dmm
Dmm
Dmm
Dmm
Dmm
Dms(sd)
Dmm(sd)
Dms
Dmm
SUNNYBROOK
Dmm(sd)
Dmm
Dms(sd,df)
Dmm(sd,df)
Sm
Dmm
Sd
Sd
Dmm(df,sh)
Si (Fm,S):sheared
Dmm
Si (F,S)
Gp
Sm,Sh,Sd
Gtg
Gh
Gt,Gp
Sh
Sr
BASE
5 m
SUNNYBROOK
ICZ
CHANNEL GRAVEL (PRF?)
SCARBOROUGH FORMATION

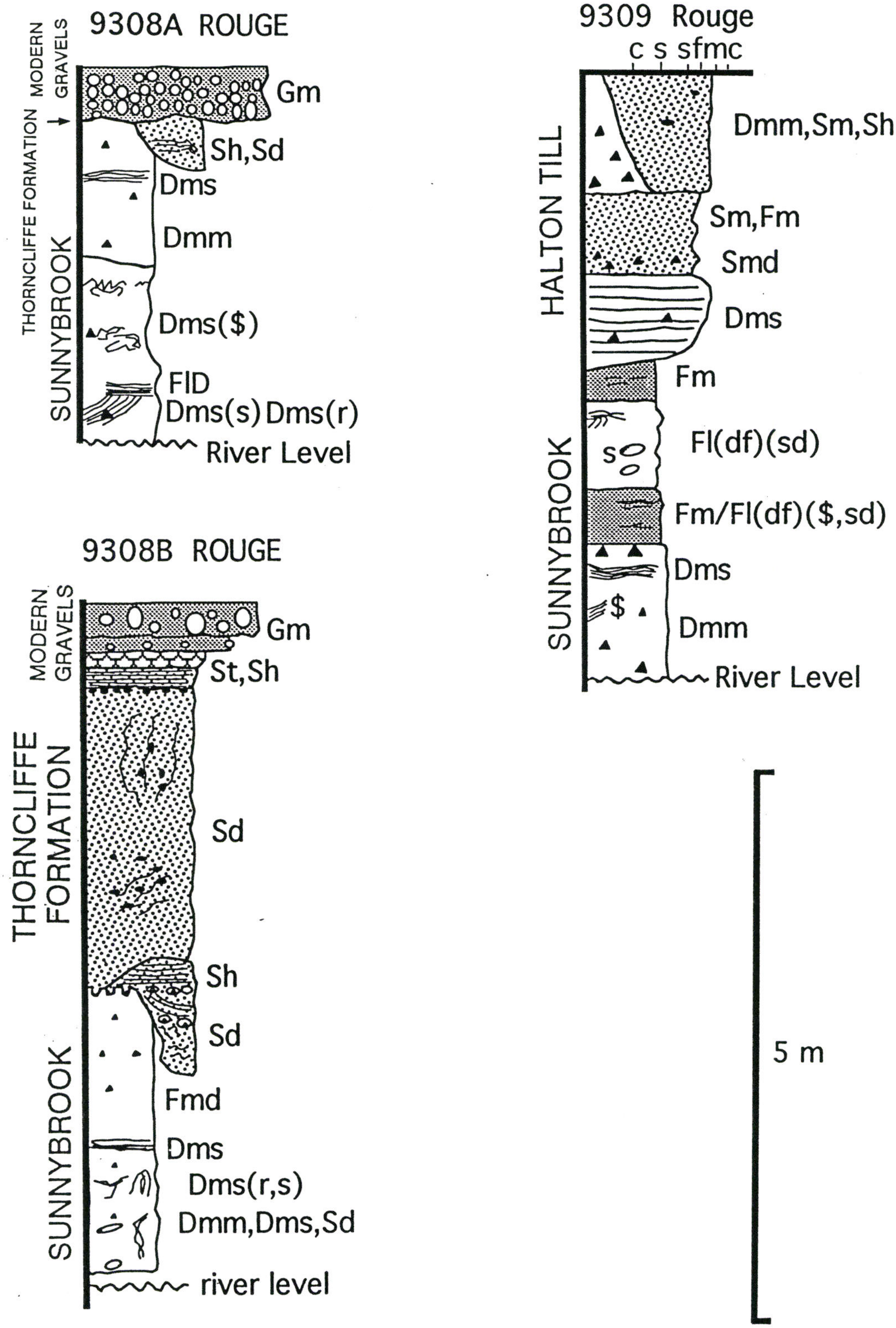

9320 BIRCHMOUNT
LK IROQ. DEPS.
SUNNYBROOK
ICZ
SCARBOROUGH FM
St
Sh,St
St
Sh
Dmm
Dms(sd)
Dms($,sd)
Si(Fl,Sd)
S
9322 WARDEN
LK IROQUOIS DEPOSITS
HALTON TILL
SCARBOROUGH FM
Sp
Sh,St
Shd
Dms
Gm
Dmm(gr)
Dmm($)
Dmm(s)
Dmm(s)
Dms(sd)
s
Dmm(s)
Sd
Si(Fm(df),Sd)
Sd
9321 CRESCENTWOOD
LK IROQUOIS DEPOSITS
HALTON TILL
SCARBOROUGH FM
St
St
Sh,Sr
Sm,Gm
Iroquois lag
Dmm
Fmd
Sd
Dm
Gm,Gg
Dms(sd)(df)
Sd
Si(Sm,Fm)(df)
Sd
5 m


9323 MORNINGSIDE
c s sfmc
soil zone
Dmm
Dms
Dmm(sd)
Sm
Sd
Dmm
Fl($)
Dmm
Dmm(sd)
Sd
Sh(sh)
Fl(sh)
HALTON TILL
c.a.
SUNNYBROOK
SCARBOROUGH FM
9325 HI Section
LK IROQUOIS DEPOSITS
THORNCLIFFE FM
St
Sh,St
Sd
Dmm
Fl(df)
Dmm
Dmm
Dmm(fractures)
Dmm
SUNNYBROOK
c.a.
ICZ
Si(Fm,Sm)
Fl(df)
Sh,Sr(sh)
Sr
Fl
Fl
Sr,Sh
SCARBOROUGH FORMATION
5 m

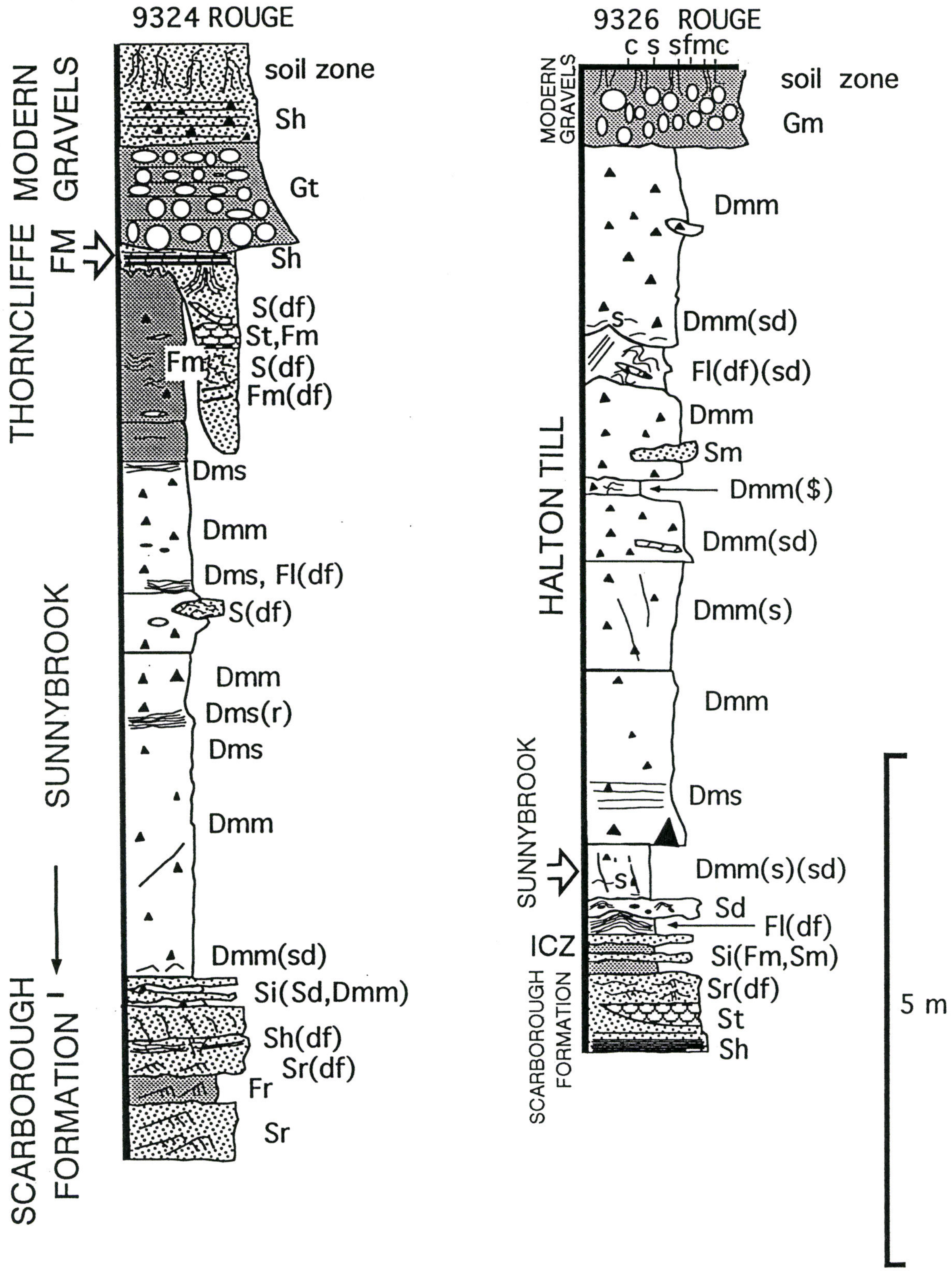


9304 ROUGE
c s sfmc
soil zone
Gm
Sh
Sd
Sh
St
Dmm
Sh,Sd,Fm
Fm(sd,$)
Fl(df)
Sd
Fm
Fl
Dmm
Dmm(sd)
Dmm
Dms
Dmm
Dmm,Fm
MODERN GRAVELS
THORNCLIFFE FM
SUNNYBROOK
9305 ROUGE
Gg
St,Sh
Dms
Sd
Dmm
Dms($)
Dms
Dmm
river level
MODERN GRAVELS
THORNCLIFFE FORMATION
SUNNYBROOK
5 m

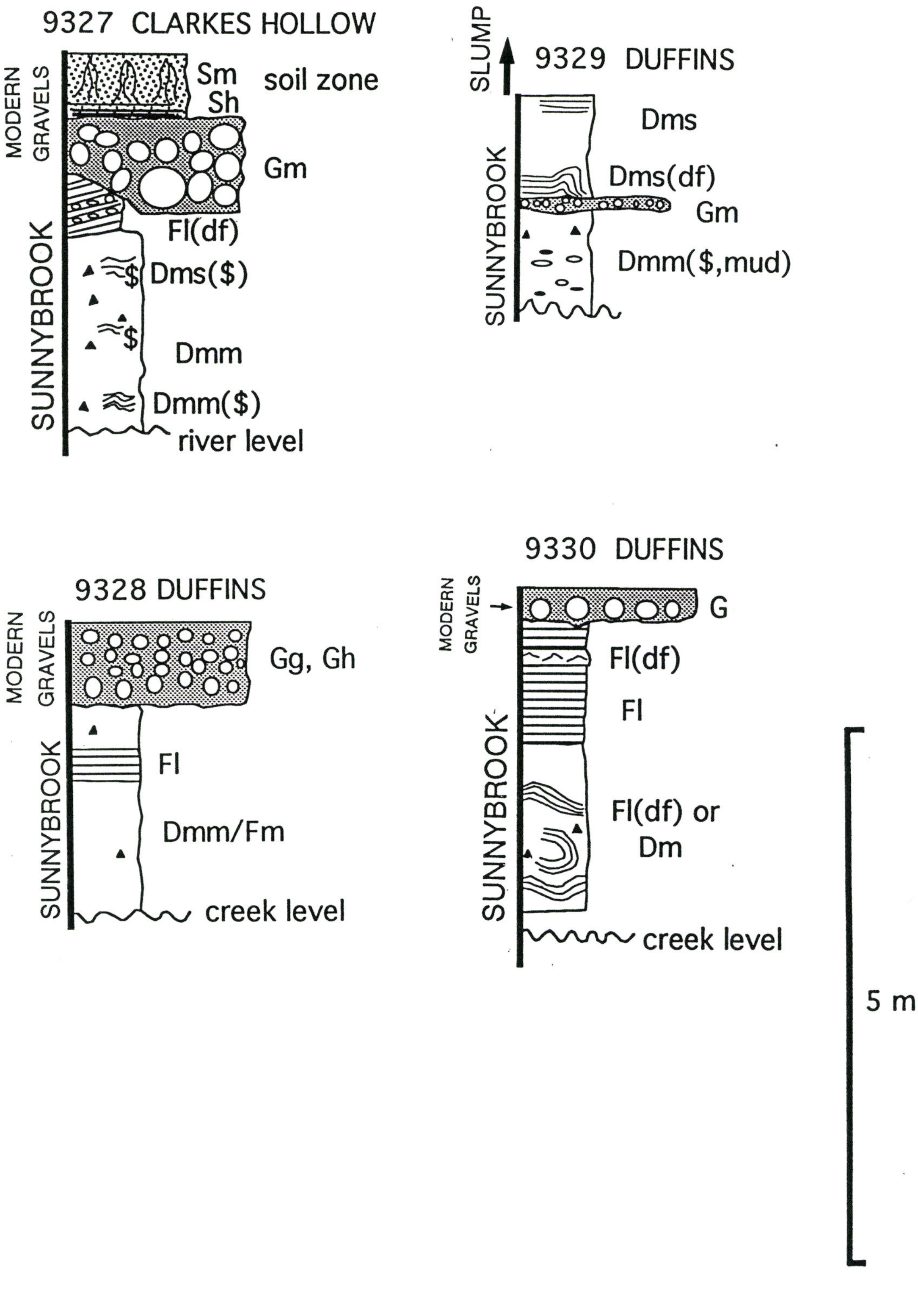

9306 ROUGE
c s sfmc
MODERN GRAVELS
Gm
THORNCLIFFE FORMATION
Sm
Sm
Sh,Sd
Dmm(sd)
Dmm
Dmm
Fl(df)
SUNNYBROOK
Dms
Dmm
Dmm
Dms
Dmm
talus
River Level
9307A ROUGE
Dmm
Sd
St
Dmm
TILL
Sm
Dmm
Dmm
Sd
Sunnybrook
Dmm(sd)
HALTON
Dmm
Dmm
River Level
9307B ROUGE
HALTON TILL
Dmm
Sd
Sm
Dmm
Si (Sm,Fm,Dm)
Sh,Sd
SUNNYBROOK
Dmm (or Fm)
Dms($)
Fm
talus
River Level
5 m



9308A ROUGE
MODERN GRAVELS
THORNCLIFFE FORMATION
SUNNYBROOK
Gm
Sh,Sd
Dms
Dmm
Dms($)
FlD
Dms(s) Dms(r)
River Level
9308B ROUGE
MODERN GRAVELS
THORNCLIFFE FORMATION
SUNNYBROOK
Gm
St,Sh
Sd
Sh
Sd
Fmd
Dms
Dms(r,s)
Dmm,Dms,Sd
river level
9309 Rouge
c s sfmc
HALTON TILL
SUNNYBROOK
Dmm,Sm,Sh
Sm,Fm
Smd
Dms
Fm
Fl(df)(sd)
Fm/Fl(df)($,sd)
Dms
Dmm
River Level
5 m



9324 ROUGE
THORNCLIFFE FM
MODERN GRAVELS
SUNNYBROOK
SCARBOROUGH FORMATION
soil zone
Sh
Gt
Sh
S(df)
St,Fm
Fm
S(df)
Fm(df)
Dms
Dmm
Dms, Fl(df)
S(df)
Dmm
Dms(r)
Dms
Dmm
Dmm(sd)
Si(Sd,Dmm)
Sh(df)
Sr(df)
Fr
Sr
9326 ROUGE
c s sfmc
MODERN GRAVELS
HALTON TILL
SUNNYBROOK
ICZ
SCARBOROUGH FORMATION
soil zone
Gm
Dmm
Dmm(sd)
Fl(df)(sd)
Dmm
Sm
Dmm($)
Dmm(sd)
Dmm(s)
Dmm
Dms
Dmm(s)(sd)
Sd
Fl(df)
Si(Fm,Sm)
Sr(df)
St
Sh
5 m



9327 CLARKES HOLLOW
MODERN GRAVELS
SUNNYBROOK
Sm
soil zone
Sh
Gm
Fl(df)
Dms($)
Dmm
Dmm($)
river level
SLUMP
9329 DUFFINS
SUNNYBROOK
Dms
Dms(df)
Gm
Dmm($,mud)
9328 DUFFINS
MODERN GRAVELS
SUNNYBROOK
Gg, Gh
Fl
Dmm/Fm
creek level
9330 DUFFINS
MODERN GRAVELS
SUNNYBROOK
G
Fl(df)
Fl
Fl(df) or
Dm
creek level
5 m

APPENDIX B:

DATA FROM TEXTURAL ANALYSES:

The following tables and graphs summarize the textural sampling completed for the Sunnybrook drift, and for relevent portions of the Halton Till, and Scarborough, Lower Thorncliffe and Lake Iroquois Formations. Facies sampled, indicating the number of analyses in parentheses, are as follows:

- Sunnybrook Dmm facies (22)
- Sunnybrook Fm,Fmd,Fl facies (6)
- Sunnybrook raft within Halton facies (1)
- Halton Till facies (5)
- Thorncliffe sand facies (9)
- Scarborough facies (3)
- Iroquois sand facies (5)

Diamict and fine-grained facies of the Sunnybrook and Halton were analyzed using a Micrometrics 500 ET Sedigraph, in lab facilities at University of Toronto (Scarborough Campus). Three samples were processed as two independent runs (indicated by * in the table), to show consistency of the texture measurement technique. Grain size curves of Scarborough, Thorncliffe, and Iroquois sediments were derived using mechanical sieving techniques at McMaster University. Sample numbers on grain size curves correspond to the following formations:

Thorncliffe Formation:
SAND 9317-1, 9306-1, 9307B-8, 9306-2, 9304-1, 9304-3, 9308B-1, 9308B-2, and 9321-2.

Scarborough Formation:
SAND 9301B-2 (Sc.Sand Fm.), 9313-5 (Sc.Clay Fm.), and 9301B-1 (suspected raft? of Scarborough sand)

Lake Iroquois sediments:
SAND 9312-1, 9312-2, 9314-1, 9314A-4, and 9314A-5.

The following table summarizes the position within the Sunnybrook from which grain size samples were taken - samples from the overlying Halton Till are clearly identified. The first four digits in the sample # refer to the section from which samples were taken. The position above the basal contact (if available) is indicated. In the absence of basal contacts, reference to stream elevations is provided. Samples along the Bluffs and dissecting creeks are assigned to the CFA based upon their location within topographic lows in the substrata.

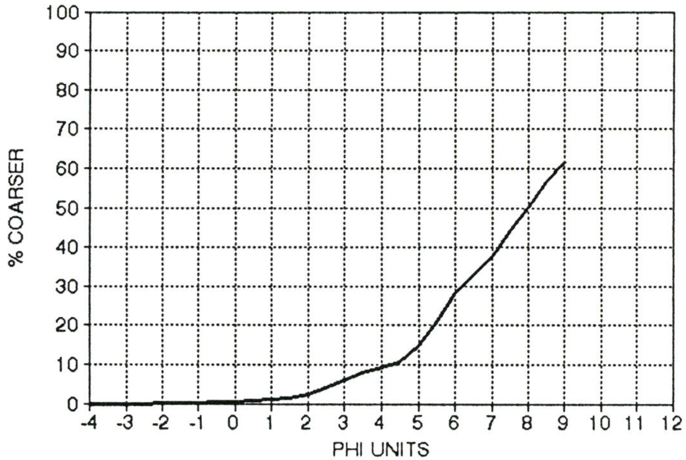
SAMPLE #	FACIES ASSOC.	SAMPLE LOCATION (from the Bluffs, unless otherwise indicated)
9301-1	HFA	· Dmm facies, 0.25 m above the Sunnybrook basal contact
9301-2	HFA	· Dmm facies, 0.5 m above the Sunnybrook basal contact
9301-3	HFA	· Dmm facies, 0.75 m above the Sunnybrook basal contact
9301-4	HFA	· Dmm facies, 1.0 m above the Sunnybrook basal contact
9301-5	HFA	· Dmm facies, 1.5 m above the Sunnybrook basal contact
9301-6	HFA	· Dmm facies, 2.25 m above the Sunnybrook basal contact
9301-7	HFA	· Dmm facies, 3.0 m above the Sunnybrook basal contact
9301-8	HFA	· Dmm facies, 3.75 m above the Sunnybrook basal contact
9301-9	HFA	· Dmm facies, 4.5 m above the Sunnybrook basal contact
9301-10	HFA	· Dmm facies, 5.25 m above the Sunnybrook basal contact
9301-11	HFA	· Dmm facies, 6.0 m above the Sunnybrook basal contact
9304-4	CFA	· (Rouge) Fm facies, 0.5m below upper contact with Thorncliffe; 10m above river level
9304-7	CFA	· (Rouge) Dmm facies, 4.25m below the upper contact with Thorncliffe; 6.25m above river level
9304-9	CFA	· (Rouge) Dmm facies, 7.75m below the upper contact with Thorncliffe; 2.75m above river level
9307B-7	HALTON	· (Rouge) Dmm facies, raft of suspected Sunnybrook within the **Halton Till**; located ≈2.6m above the Halton-Sunnybrook contact
9307B-9	CFA	· (Rouge) Fm/Dmm facies, 0.5m below contact with the Halton, 2.2m above river level
9308B-3	CFA	· (Rouge) Fmd/Dmm facies, 0.5m below contact with the Thorncliffe, 2.3m above river level
9309-3	HALTON	· (Rouge) Dms facies (**Halton Till**), 0.75m above the contact with Sunnybrook, 3.4m above river level
9309-4	CFA	· (Rouge) Dmm facies, 0.3m below contact with Halton Till, 2.5m above river level

9312-3	HALTON	· Dmm facies (**Halton Till**), 1.6m above the basal contact with the Scarborough Formation
9312-4	HALTON	· Dmm facies (**Halton Till**), 0.15m above the basal contact with the Scarborough Formation
9313-2	HFA	· Dmm facies, diamict diapir amongst sand pillows of the overlying Thorncliffe formation, i.e. at the Sunnybrook upper contact
9315-1	CFA	· Fld facies, from ≈1m above the contact between laminated and diamict facies, 3.8m above the Sunnybrook basal contact
9315-2	CFA	· Dmm facies, 0.5m above the basal contact with the Scarborough Formation
9315-3	CFA	· Dmm facies, 2.4m above the basal contact with the Scarborough Formation
9324-1	CFA	· (Rouge) Fm facies, 1.25m below upper contact with the Thorncliffe Formation, ≈9.5m above river level
9325-2	HFA	· Dmm facies; 4.5m below upper contact with Thorncliffe Formation; 3.25m above basal contact with Scarborough Formation
9326-1	CFA	· (Rouge) Dmm(s) facies, 0.25m above basal contact with Scarborough Formation, 0.35m below upper contact with Halton Till
9327-1	CFA	· (Duffins) Dmm facies, 1.5m below upper contact with Holocene gravels, 0.8m above creek level
J94-1	CFA	· (Duffins) Dmm facies, ≈1m above creek level

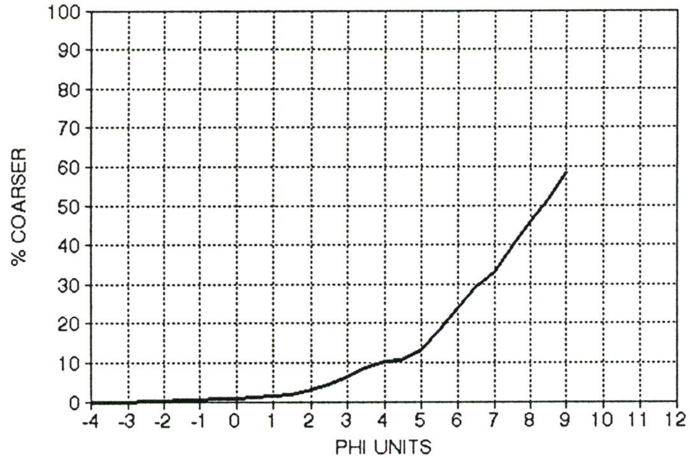
Diamict Grain Size Raw Data, sediment unit and facies ar indicated (if known). RUN 2 on 13 Dec 1993					
Sample ID	**unit**	**facies**	**% sand**	**% silt**	**% clay**
9301-1	Sunnybrook	Dmm	28.6	31.4	40.0
9301-2	Sunnybrook	Dmm	9.6	39.8	50.6
9301-3	Sunnybrook	Dmm	10.5	53.7	35.8
9301-4	Sunnybrook	Dmm	12.5	41.1	46.4
9301-5	Sunnybrook	Dmm	10.6	55.4	34.0
9301-6	Sunnybrook	Dmm	13.7	47.5	38.9
9301-7	Sunnybrook	Dmm	11.4	51.0	37.7
9301-8	Sunnybrook	Dmm	12.4	53.4	34.1
9301-9	Sunnybrook	Dmm	12.7	53.3	34.0
9301-10	Sunnybrook	Dmm	12.3	40.3	47.3
9301-11	Sunnybrook	Dmm	4.0	48.0	48.0
9304-4	Sunnybrook	Fm	0.7	39.2	60.1
9304-7	Sunnybrook	Dmm	16.6	38.4	45.0
9304-9	Sunnybrook	Dmm	7.6	47.1	45.3
9307B-7	SB raft(?)	Dmm	19.4	34.3	46.4
9307B-9	Sunnybrook	Fm	0.4	44.3	55.3
9308B-3	Sunnybrook	Fmd	1.6	46.3	52.2
9308B-3*	Sunnybrook	Fmd	0.9	36.7	62.5
9309-3	Halton	Dms	52.7	16.1	31.2
9309-3*	Halton	Dms	52.9	26.4	20.7
9309-4	Sunnybrook	Dmm	0.7	48.7	50.6
9312-3	Halton	Dmm	38.7	31.6	29.7
9312-3*	Halton	Dmm	40.4	23.2	36.4
9312-4	Halton	Dmm	37.0	26.1	36.8
9313-2	Sunnybrook	Dmm	17.1	47.6	35.2
9315-1	Sunnybrook	Fld	2.1	46.0	51.9
9315-2	Sunnybrook	Dmm	55.9	22.9	21.2
9315-3	Sunnybrook	Dmm	46.9	25.2	27.9
9324-1	Sunnybrook	Fm	2.0	31.4	66.6
9325-2	Sunnybrook	Dmm	13.0	42.6	44.4
9326-1	Sunnybrook	Dmm(s)	10.2	44.0	45.8
9327-1	Sunnybrook	Dmm	24.9	30.0	45.1
9327-1*	Sunnybrook	Dmm	25.4	34.3	40.3
J94-1	Sunnybrook	Dmm	24.0	34.2	41.8

* NOTE: section J94-1 is equivalent to log 9328 (this study).

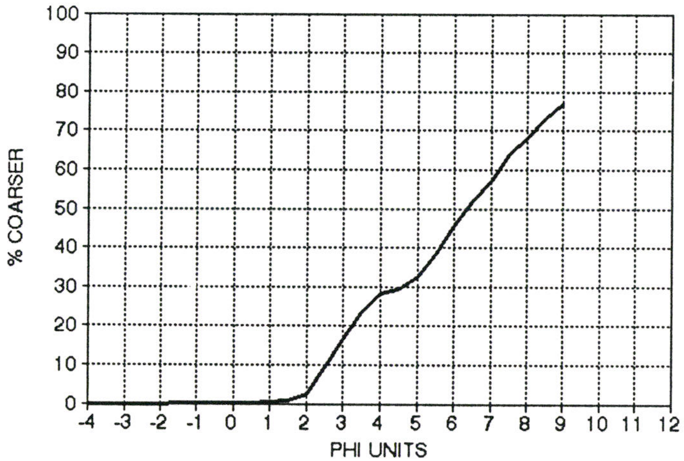
DIAMICT 9301-2



DIAMICT 9301-3



DIAMICT 9301-1



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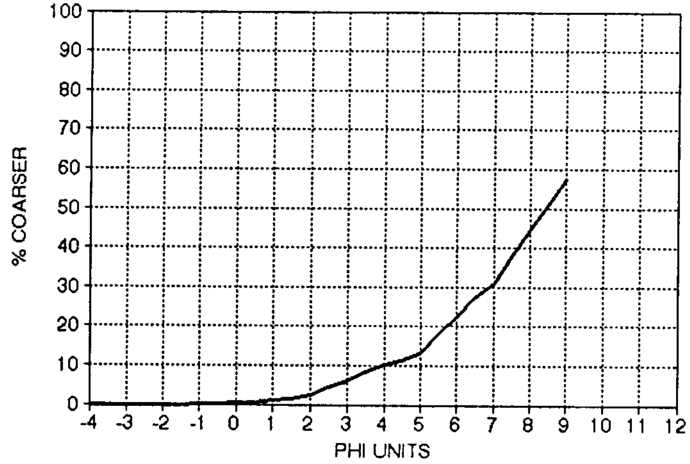
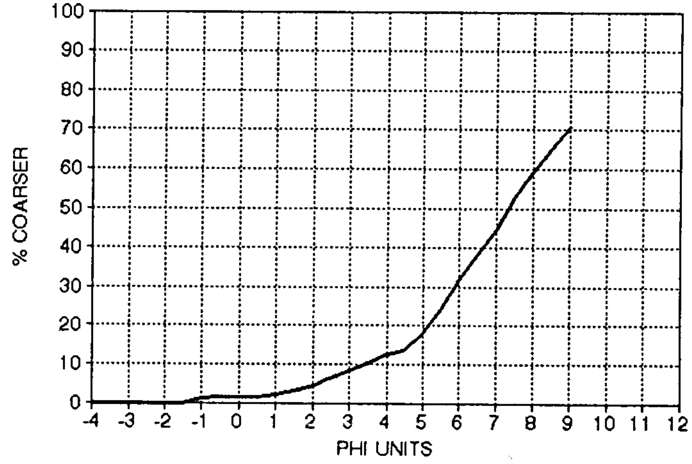


DIAMICT 9301-4



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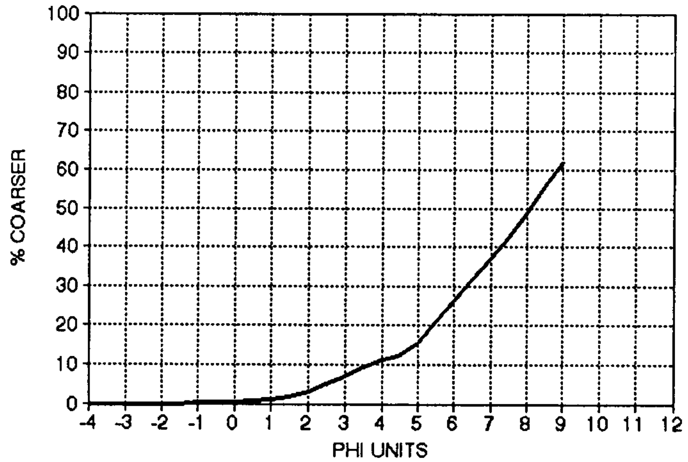
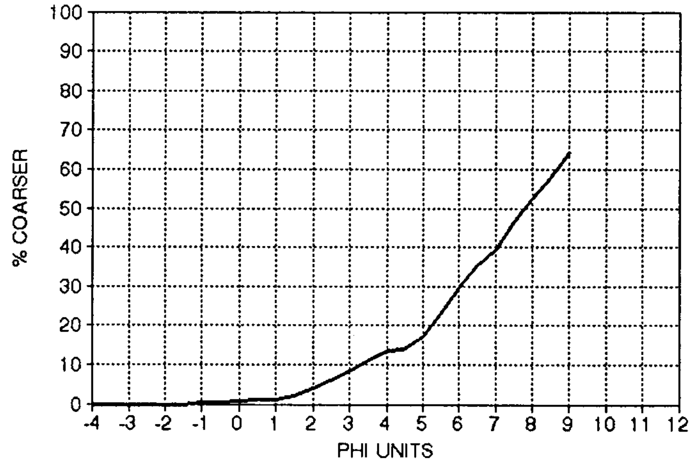
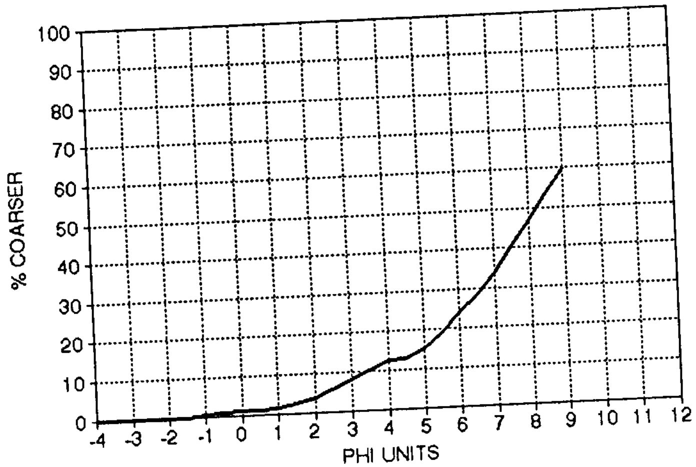


DIAMICT 9301-6



DIAMICT 9301-9



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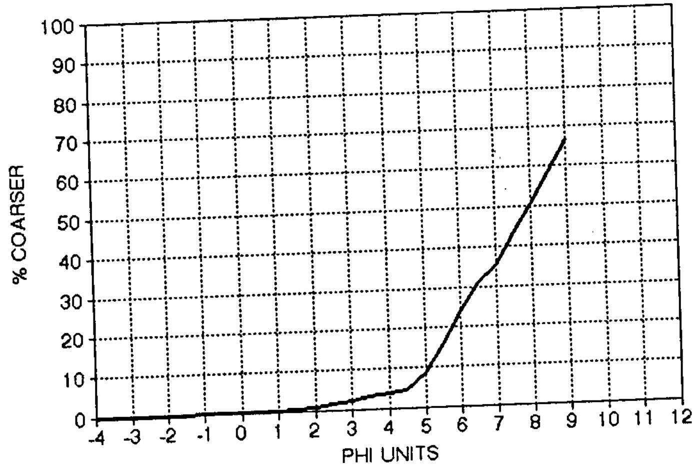
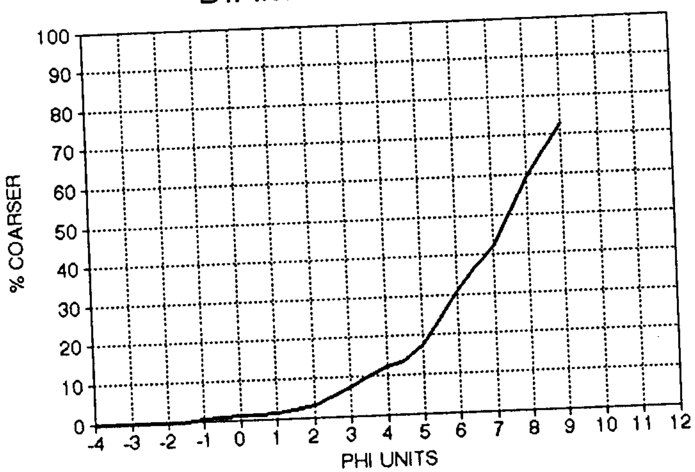
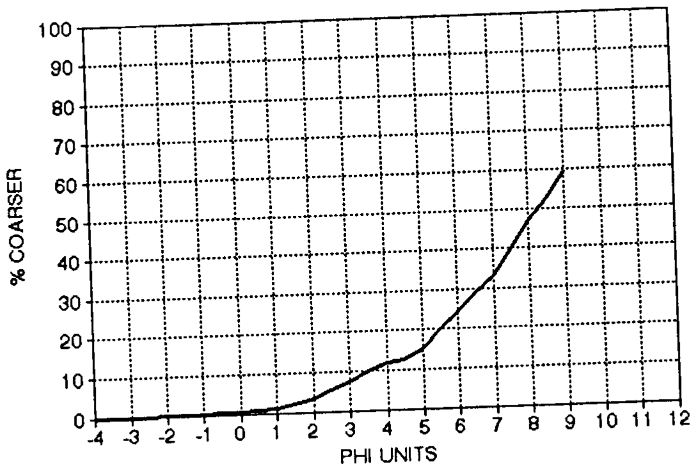


DIAMICT 9301-10



DIAMICT 9301-8



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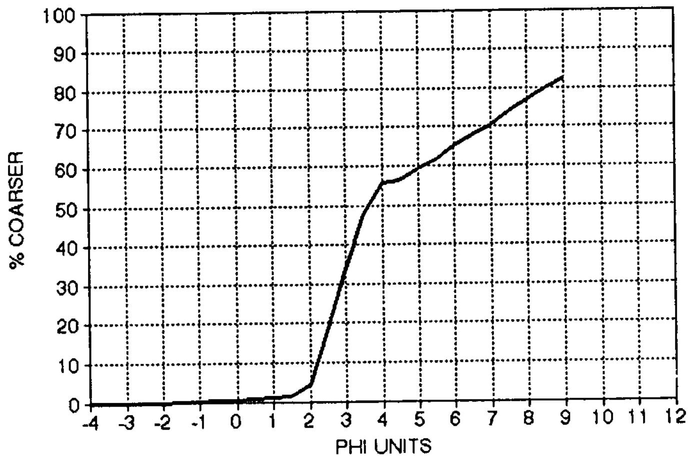
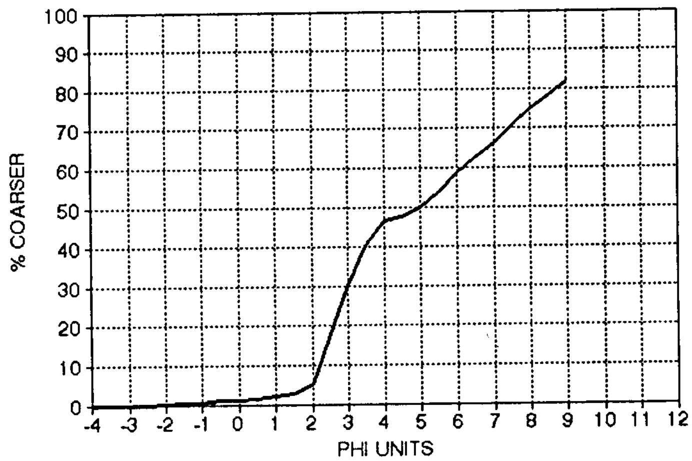
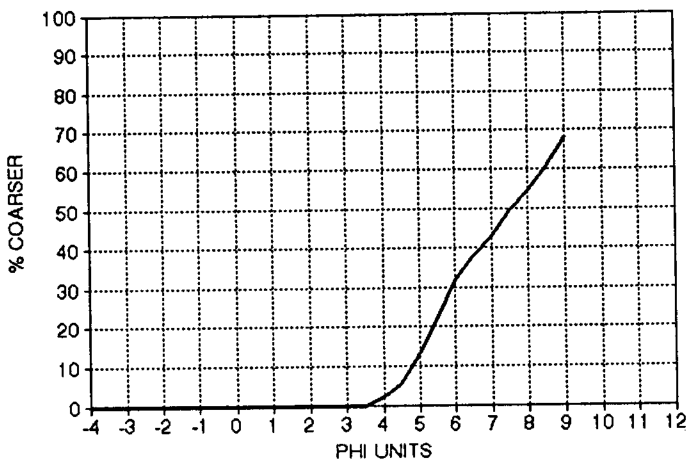


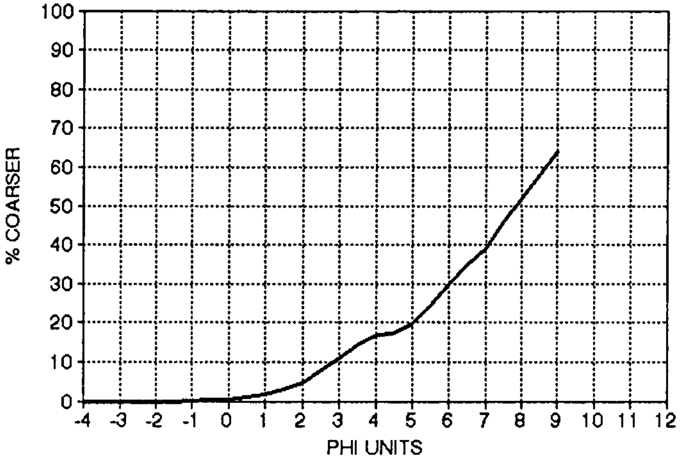
DIAMICT 9315-3



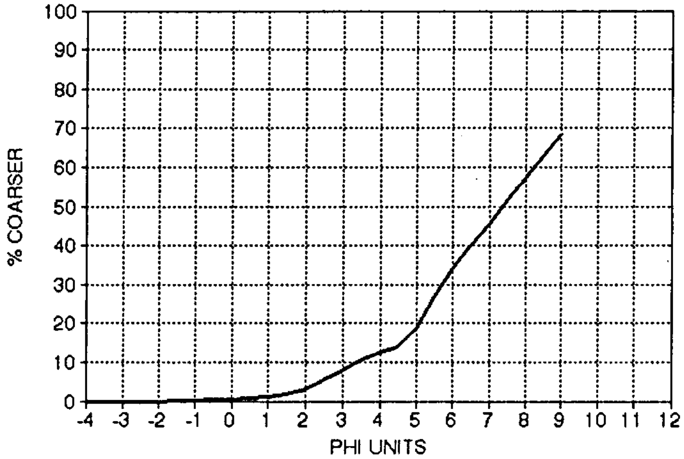
DIAMICT 9315-1



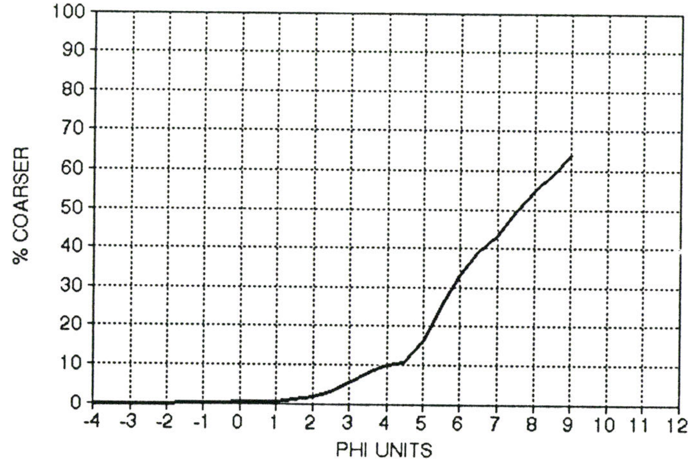
DIAMICT 9313-2



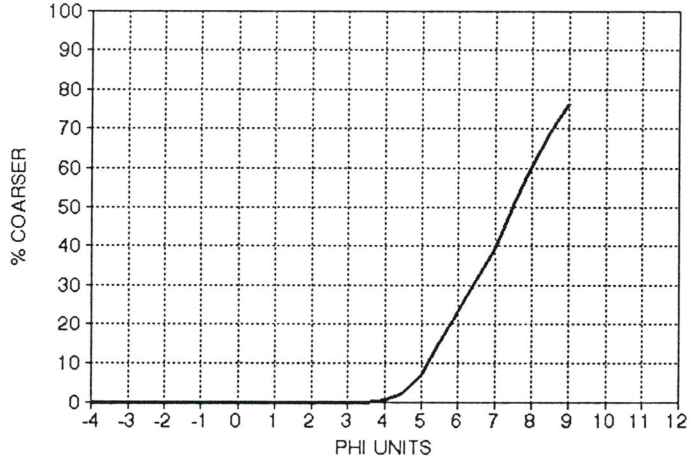
DIAMICT 9325-2



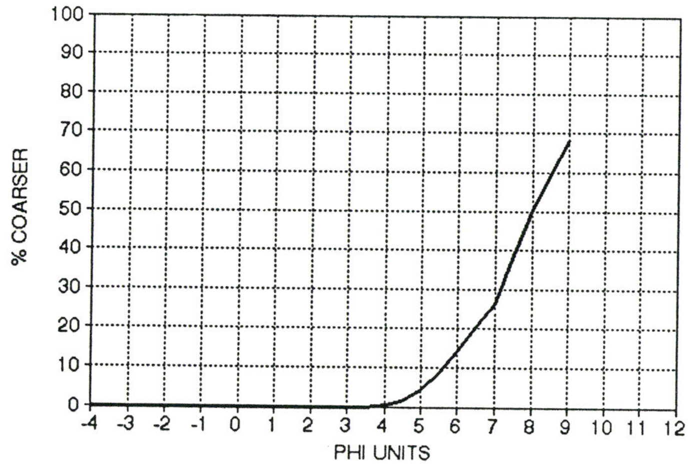
DIAMICT 9326-1



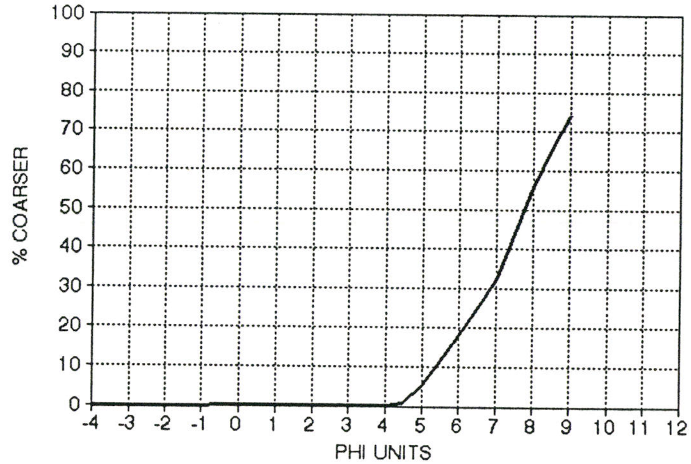
DIAMICT 9304-4



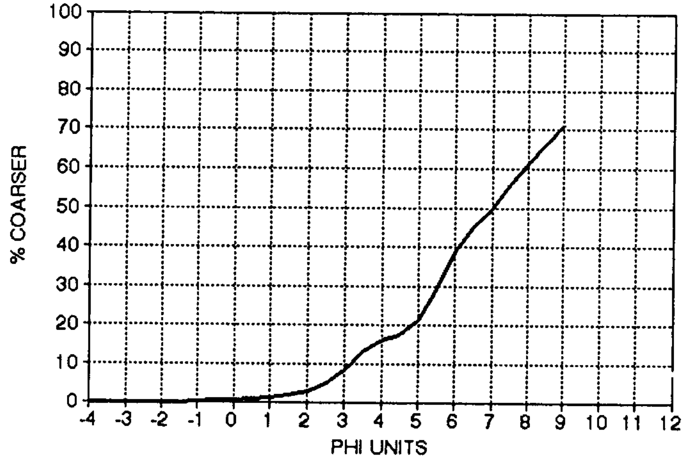
DIAMICT 9309-4



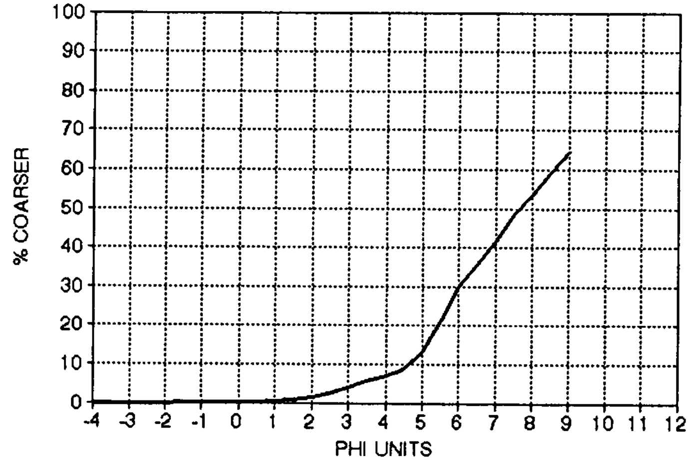
DIAMICT 9307B-9



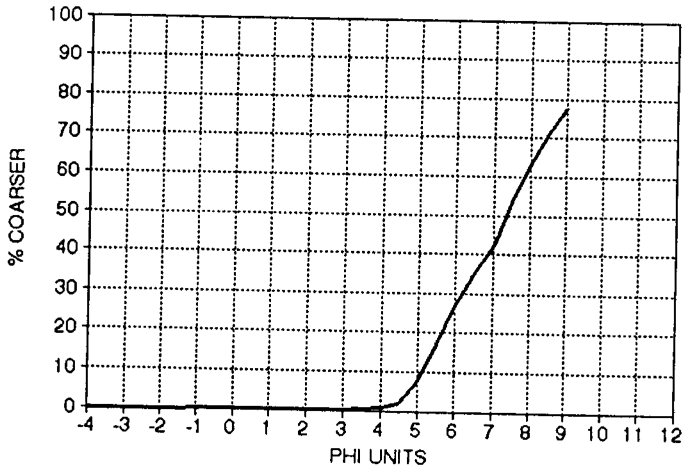
DIAMICT 9304-7



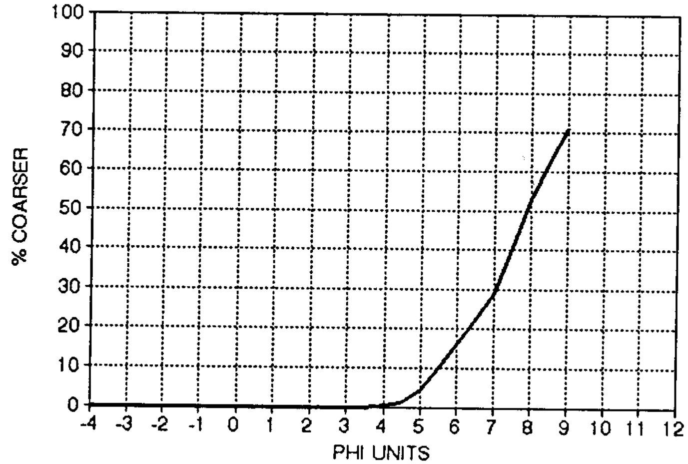
DIAMICT 9304-9



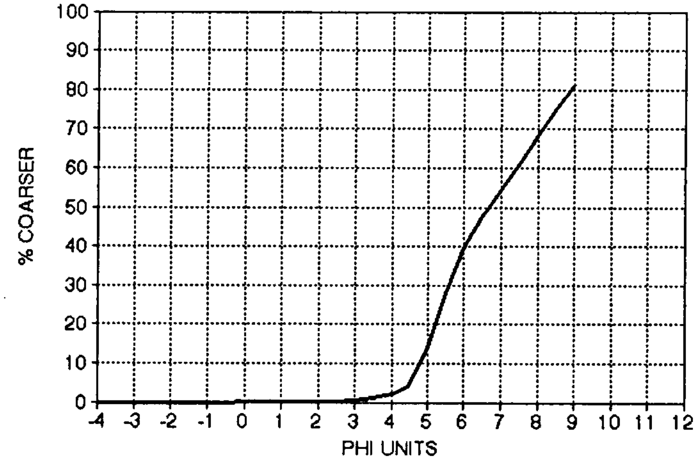
DIAMICT 9308B-3*



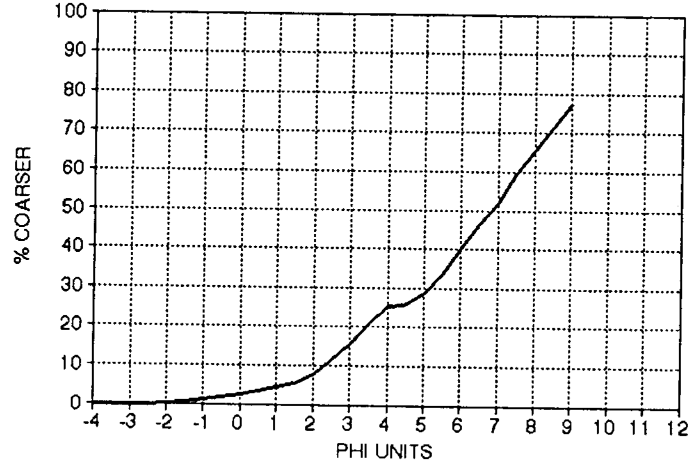
DIAMICT 9308B-3



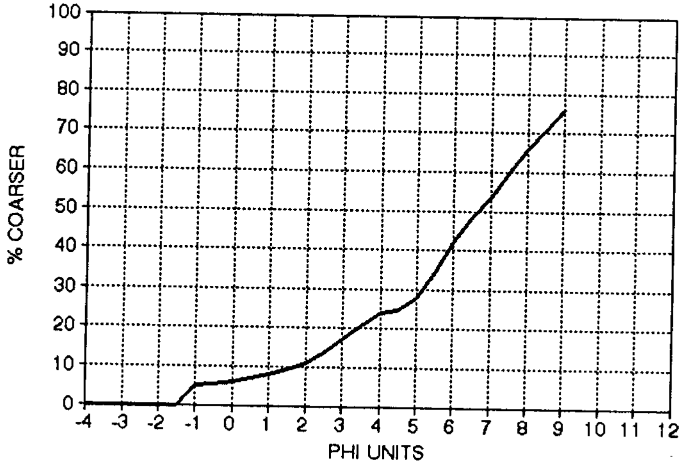
DIAMICT 9324-1



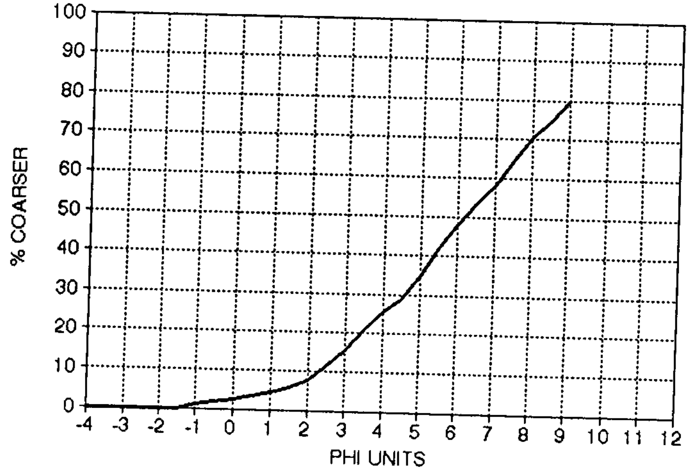
DIAMICT 9327-1*



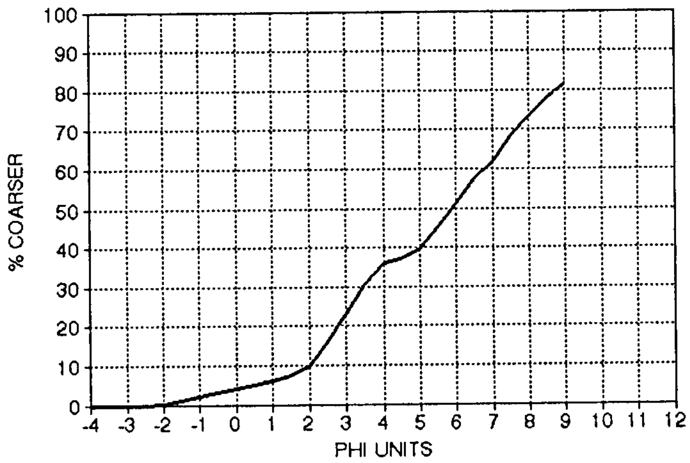
DIAMICT J94-1



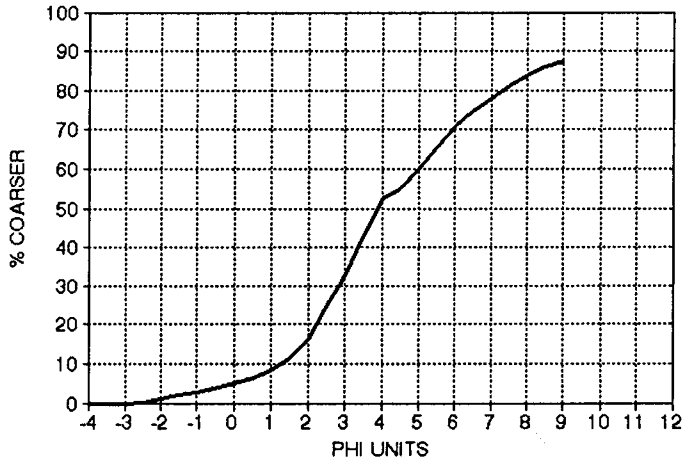
DIAMICT 9327-1



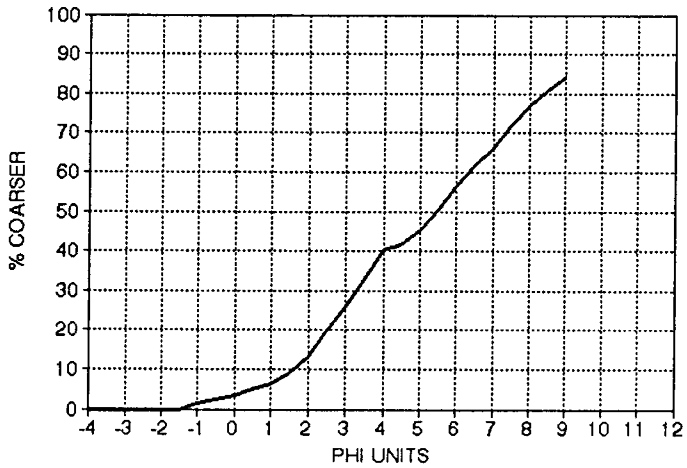
DIAMICT 9312-4



DIAMICT 9309-3



DIAMICT 9312-3*



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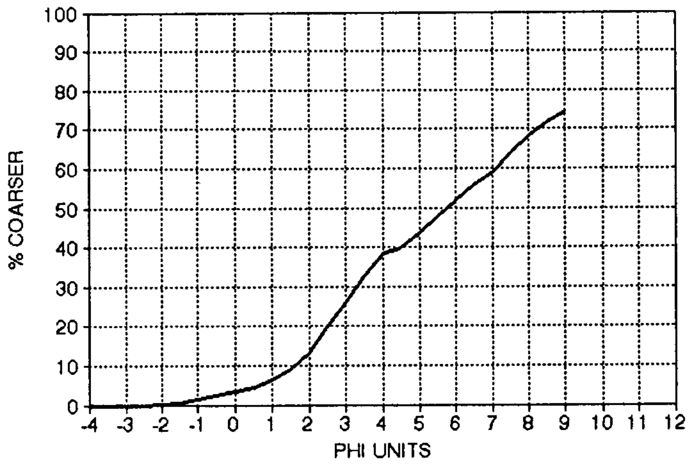
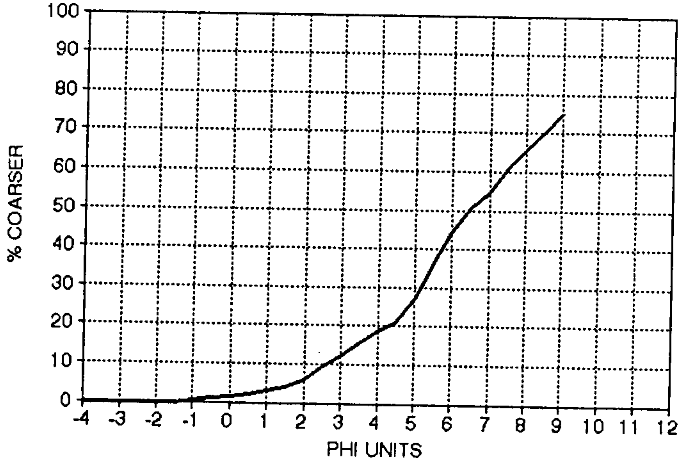
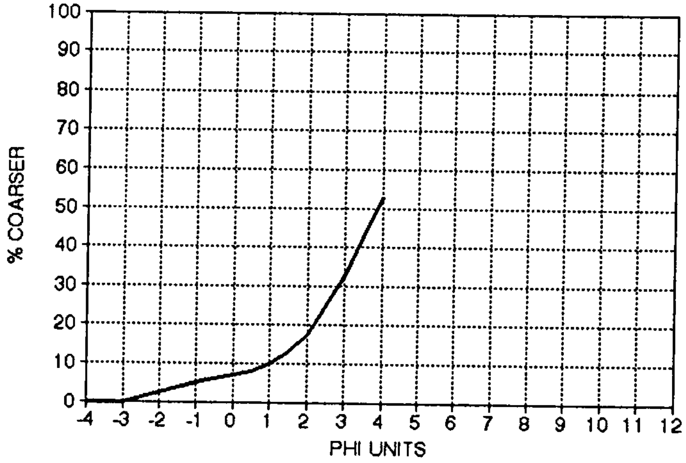


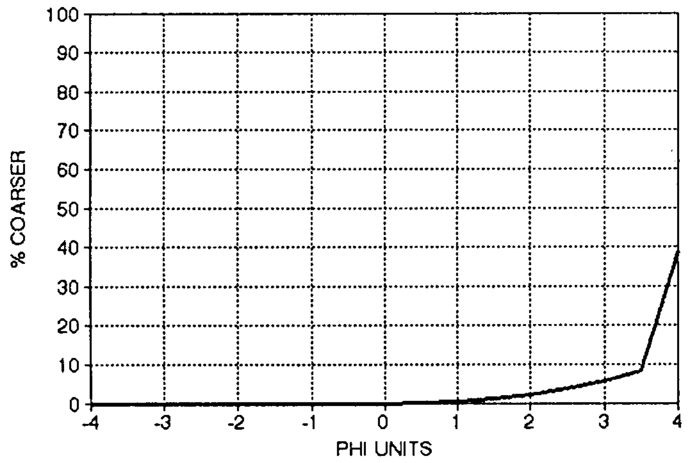
DIAMICT 9307B-7



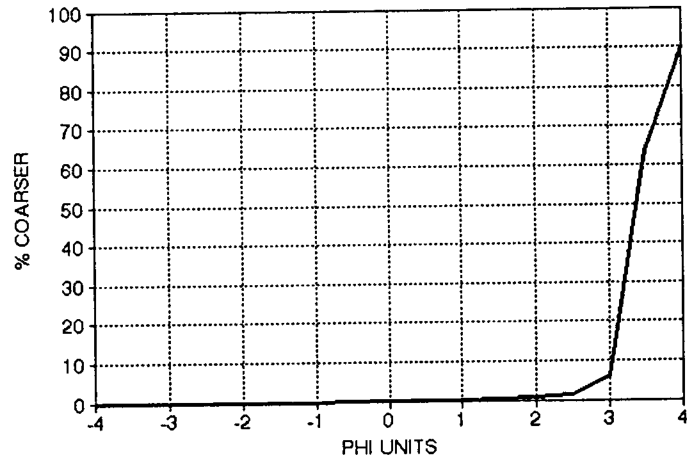
DIAMICT 9309-3*



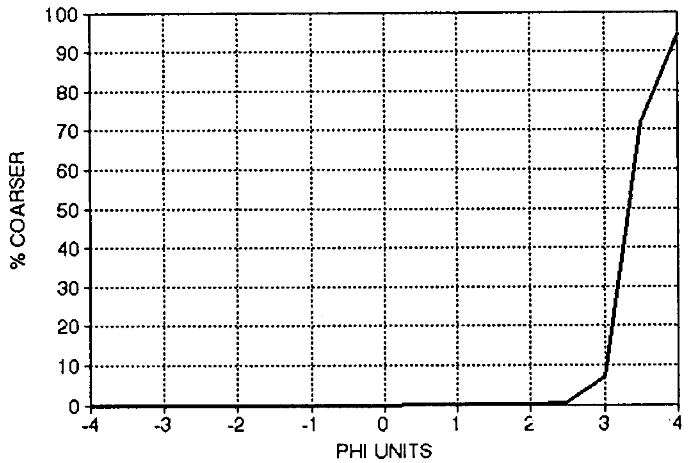
SAND 9304-1



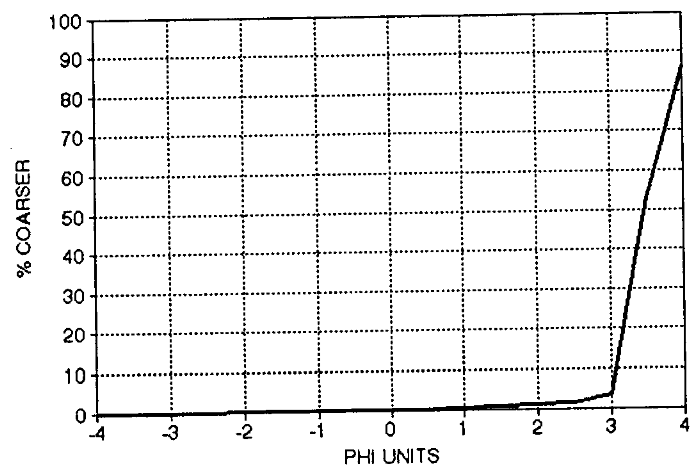
SAND 9308B-1



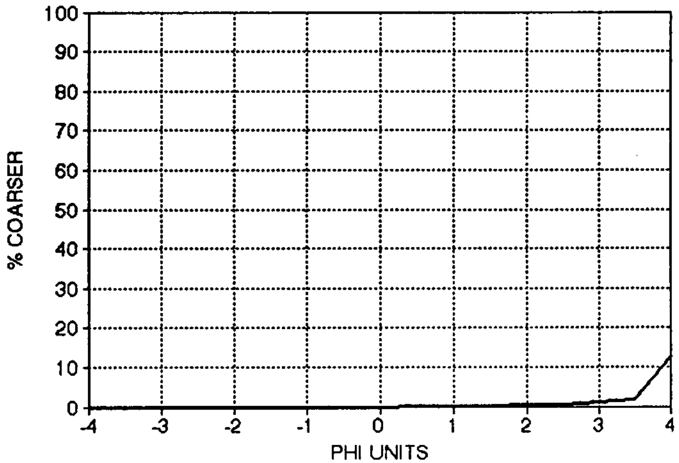
SAND 9304-3



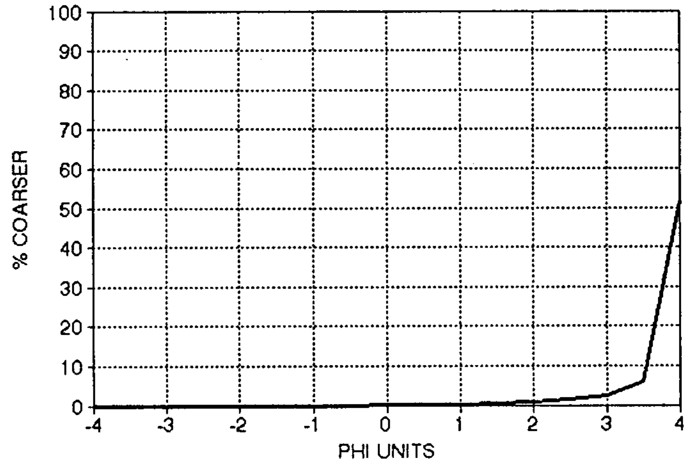
SAND 9308B-2



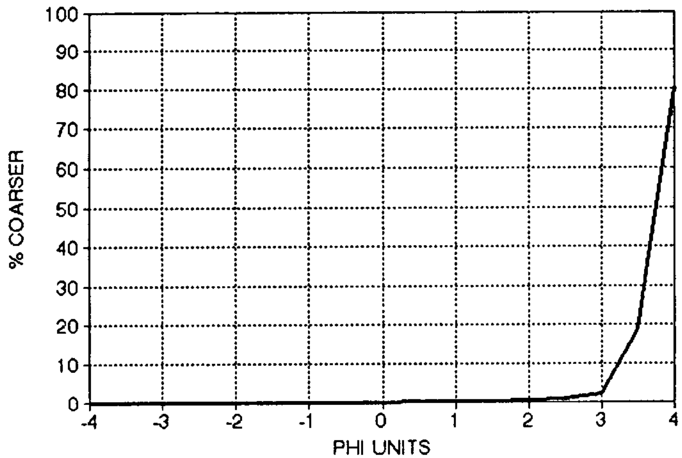
SAND 9317-1



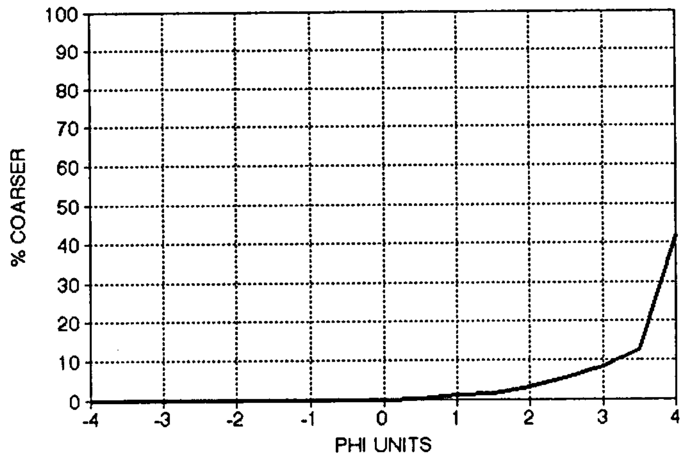
SAND 9306-1



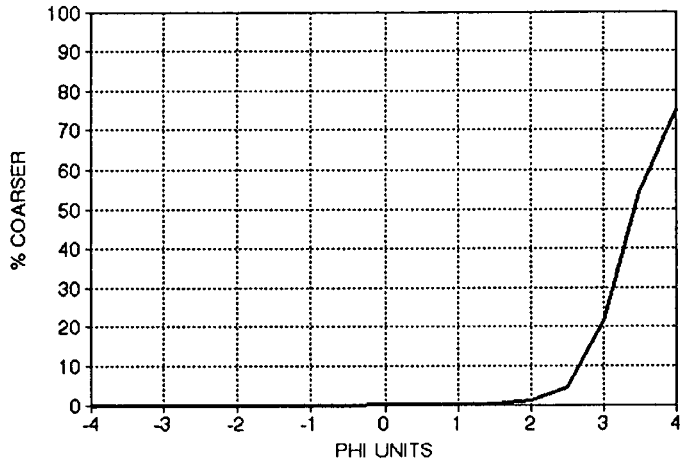
SAND 9307B-8



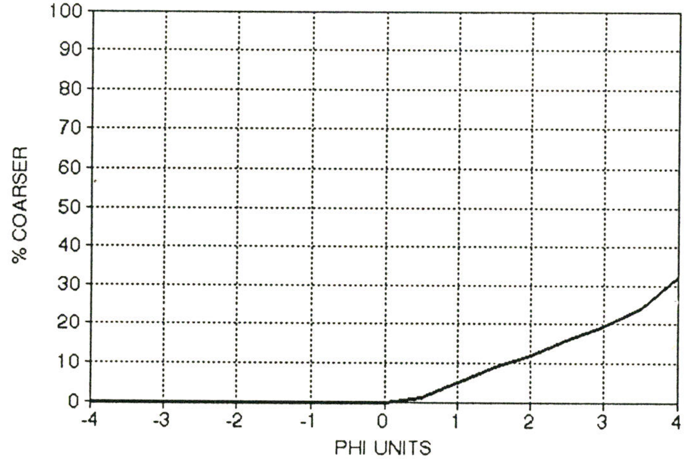
SAND 9306-2



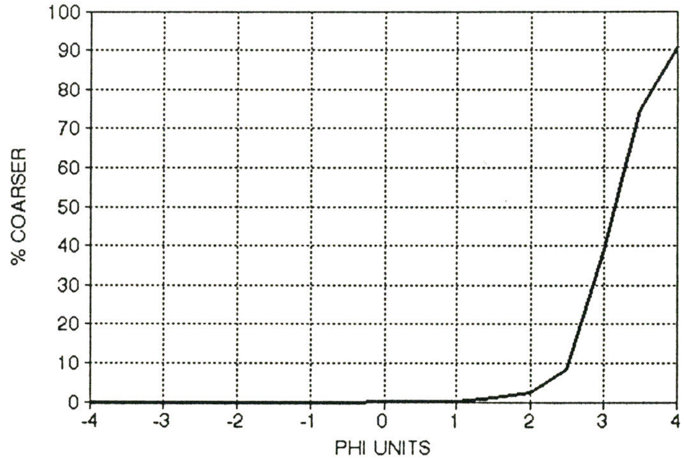
SAND 9321-2



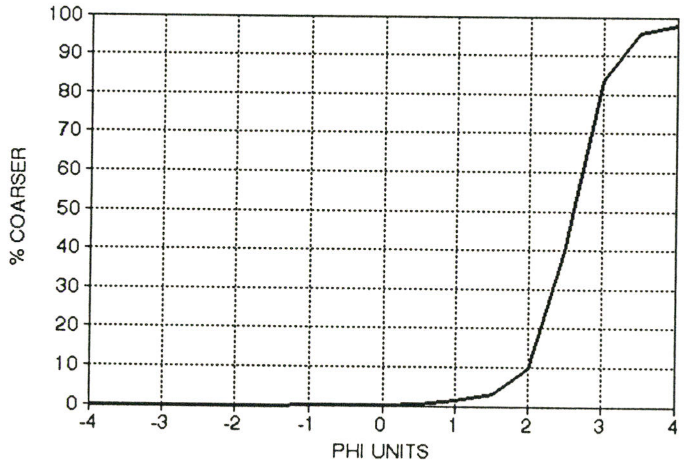
SAND 9313-5



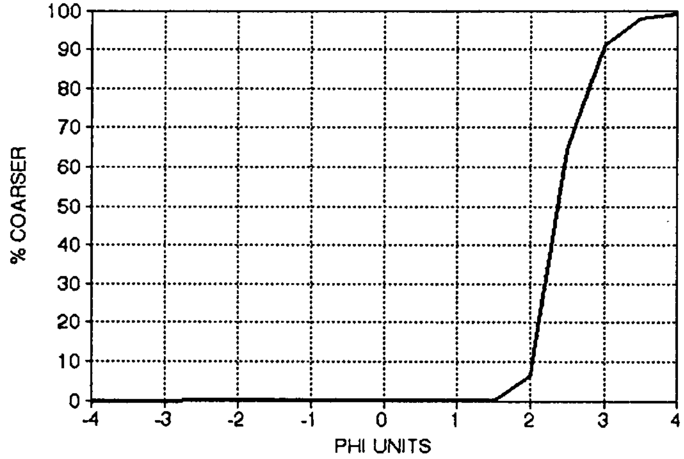
SAND 9301B-2



SAND 9301B-1



SAND 9312-2



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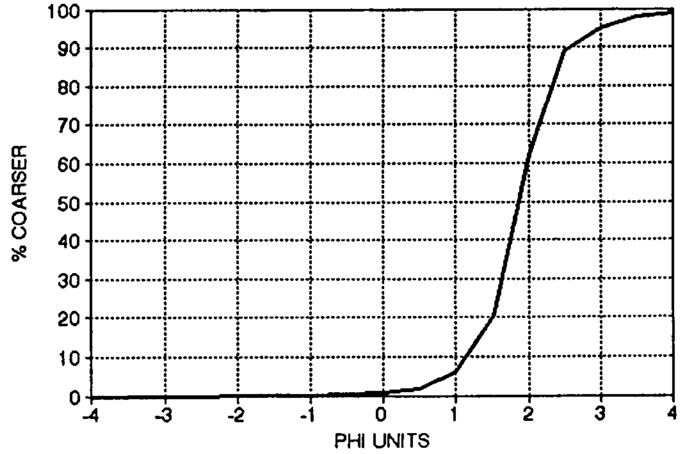
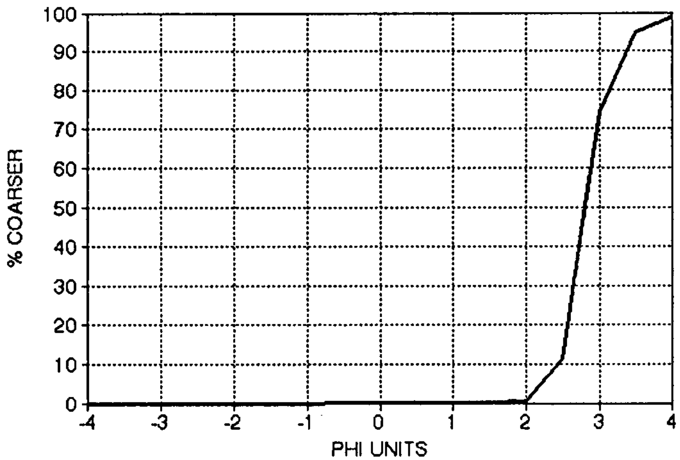
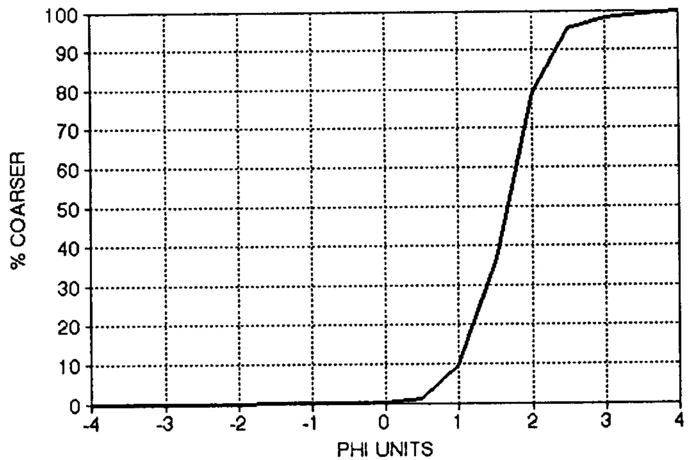


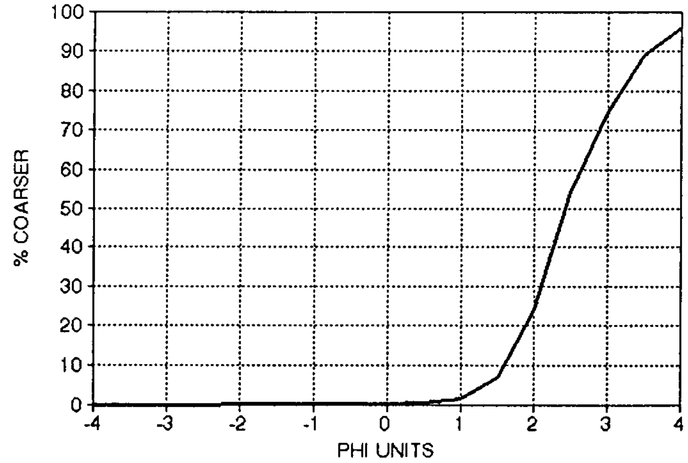
SAND 9312-1



SAND 9314-1



SAND 9314A-4



APPENDIX C:

SECTION NAMES AND EQUIVALENTS TO PREVIOUS STUDIES

site no. (this study)	site name (this study)	Karrow (1967)	Eyles (1982)	Hicock/Dreimanis (1992a)
9301	Sylvan Park East	≈A1016	2581	6
9302	Sylvan Park West	≈A1016	2581	5
9303A	Dutch Church	A1008	1681 C,D,E	
9303B	Bluffers Park	A1009	1681 C,D,E	1, ≈2
9311	Guild Inn	A1022		
9312	Birchcliff			
9313	Cathedral Bluffs	A1013 & A1011	0681 & 1281	3
9314	Springbank Ave		1881B	
9314A	Rosetta McCrain			
9315	Midland Ave	A1005		
9316	Valhalla Blvd			
9317	Cudia Park	≈A1012	2081	4
9318	Livingstone Road	A1019	2381	
9320	Birchmount Road			
9321	Crescentwood Road	A1002	1981	
9322	Warden Ave	≈A1001		
9323	Morningside Ave	A1024		
9325	HI Section	A1014	1481	
9304	Rouge	F114		
9305	Rouge	F112		
9306	Rouge	F111		
9307A,B	Rouge	F113		
9308A,B	Rouge	F21		
9309	Rouge	F110		
9324	Rouge	F116		
9326	Rouge	F119		
9327	Duffins	J98		
9328	Duffins	J94		
9329	Duffins	---		
9330	Duffins	---		

APPENDIX D:

FABRIC DATA FOR CLASTS IN BASAL CLAST HORIZONS, IN THE SUNNYBROOK DIAMICT

TABLE D.1: Clast fabric data for 'prolate clasts' measured in the present study. These have an a/b axial ratio greater than 1.4; hence, they are suitable for fabric analyses (Rappol, 1985). A- and b-axes lengths are the major axes lengths for each clast. Orient 1 (in degrees) refers to the measured 'downdip' orientation of the clast major (a-axis); a second orientation (orient 2) is indicated if the clast has no dip (note, on **Fig.2.9**, both orient 1 and orient 2 are plotted for zero dip clasts). The orientation and dip of any striations on the clasts is indicated in the two columns on the right side of the table. **Table D.2** has similar headings.

a-axis (cm)	b-axis (cm)	orient 1(°)	orient 2(°)	dip(°)	orient striae	dip striae	site no.
20.3	12.7	239	059	0			9301
12.7	7.6	226	046	0			9301
10.2	5.1	271		10			9301
5.1	2.5	261	081	0			9301
10.2	6.4	226		8			9301
8.9	6.4	238		15			9301
4.4	3.2	343	163	0			9301
26.7	15.2	277		6			9301
12.7	7.6	291		10	criss-crossing		9301
8.9	6.4	226	046	0			9301
11.4	7.6	231	051	0	criss-crossing		9301
7.6	5.1	246		10			9301
3	2	214	034	0			9301
5	3	290	110	0			9301
8	4	241	061	0			9301
8	5	311		22			9301

4.5	2	296		6			9301
9	4	248	068	0			9301
3	1.5	180		14			9301
17	11	323		2			9301
21	13	239	059	0			9301
4	2	258	078	0	258	0	9301
4	2.5	286		10			9301
6.5	4	285	105	0			9301
26	14.5	097		4			9301
5	3.5	214	034	0			9301
9.5	5	44		10			9301
9.5	4.5	275		28			9301
2.5	1.5	209	029	0			9301
4.5	2.5	178		20	40	20	9301
3.5	2.5	204	024	0			9301
3	1.5	231	051	0			9301
8	5	245		10	245	10	9301
5.5	3	288	108	0	288	0	9301
17	10.5	185		8			9301
22	13	190		5	255	5	9301
5.5	3.5	285	105	0			9301
4	2	074		8	74	8	9301
4	2.5	219	039	0			9301
11	8	173		9			9301
4	2	230	050	0			9301
25	17	302	122	0			9313
11	7.5	034		12			9314
17	12.5	071		8	161	0	9314
5.5	4	088		40			9314
8	4	050		24			9314
7	4	127		9			9314

10	7	261	081	0			9323
21	13	250		60	250	60	9323
23	16	242	062	0			9323
19	10	240		16			9323
36	20	209	029	0			9323
10	6	354	174	0			9317
11	7.5	080		10			9317
9.5	6.5	307	127	0	307	0	9317
11	7	133		6			9317
7	3.5	258	078	0			9317
3.5	2.5	248	068	0			9317
6	4	234	054	0			9317
5	3	248	068	0	248	0	9317
5.5	4	103		10			9317
6.5	3	226	046	0	256	0	9317
10	5.5	359		8			9317
5.5	4	336	156	0			9317
5	3.5	360	180	0			9317
8	5.5	178		29			9317
12.5	9	351	171	0			9317
15.5	11	103		6			9317
5.5	3.5	078		6			9317
12	6.5	207		18			9317
5.5	3	059		14			9317
5	3.5	279	099	0			9317
7	3.5	245	065	0			9317
6	3.5	186	006	0			9317
5	3	135		22	135	22	9317
13	7	302	122	0			9325
16	11	326		6			9325
11	7	120		22			9325

13	9	076		22			9325
8	5	307	127	0			9325
11	5	108		14	108	14	9325
11	6	206		12			9325
7	5	057		11			9325
7.5	5	045		8			9325
7	4.5	290	110	0			9325
9	4	084		12	094	10	9325
9	6.5	267	087	0			9325
7.5	4	334		13			9325
13.5	9	103		11			9325

TABLE D.2: Clast fabric data for non-'prolate clasts' measured in the present study. These have an a/b axial ratio less than 1.4, unsuitable for fabric analyses (Rappol, 1985), and therefore, were not analyzed in the present study. Refer to **Table D.1** for description of column headings.

a-axis	b-axis	orient 1	orient 2	dip	orient striae	dip striae	site no.
6.4	5.1	279	099	0			9301
17.8	14	331	151	0			9301
6.4	5.1	271	091	0	criss-crossing		9301
9	7	224		8			9301
10	8	284	104	0			9301
8	6	277	097	0			9301
17	14	190	010	0			9301
8	7	256	076	0	256	0	9301
4.5	3.5	66		14			9301
4	3	131		14			9301
3	2.5	314		30			9301
2.5	2	183	003	0	183	0	9301
7	5.5	339	159	0			9301
8	6	242	062	0			9301
5	4	212	032	0			9301
18.5	14.5	014		12			9313
9	8	232	052	0			9313
4.5	3.5	324	144	0			9314
17	14	240	060	0			9314
21	18	110		14	110	14	9314
18	15	314	134	0	criss-crossing		9323
4.5	3.5	130		6			9323
20	15	236		6			9323
10	8	239	059	0			9323
9.5	8	270	090	0	270	0	9317

6	5	353		6			9317
10	7.5	267	087	0			9317
7.5	6	356		7	356	7	9317
6	4.5	199	019	0			9317
19	16	359		12	criss-crossing		9317
6	4.5	076		22	076	22	9317
17.5	13.5	270		10	270	10	9317
2nd set of striae for above clast					180	0	
21	17	160		11			9317
10.5	9	009		12			9317
6	5	120		14			9317
8	7	057		19	057	19	9325
8	5.5	237	057	0	237	0	9325
8.5	7	250	070	0	070	0	9325
14.5	11	360	180	0			9325
8	6	111		4			9325
5	4	050		24	criss-crossing		9325
4.5	4	134		8			9325
18	16	240		4			9325
5.5	4.5	294	114	0	264	0	9325
6	4.5	256	076	0			9325
14.5	11.5	061		5			9325