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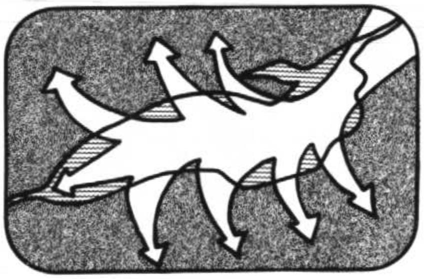

The Application of Basin Analysis Techniques to Glaciated Terrains: An Example from the Lake Ontario Basin, Canada

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Introduction

This report is the first of two designed to demonstrate how the subsurface investigation of a major glaciated basin across some 7000 km² of southern Ontario is currently a valuable focus for interdisciplinary geoscience.

Subsurface facies mapping, using geophysical well logs calibrated against surface exposures, is not only providing new data regarding Quaternary sedimentation and the history of the Great Lakes, but is also yielding significant information for applied projects in connection with hydrocarbon resources in Pre-Quaternary glacial basins, offshore engineering, mineral exploration and groundwater resource evaluation. A subsequent article will detail the value of this basin reconstruction for applied projects in Metropolitan Toronto and the nearby region, principally in connection with stabilization of over 10 km of actively-eroding lakeshore bluffs along Lake Ontario.

Rationale

During the last twenty years the science of sedimentology has undergone a revolution, largely because of the development of facies analysis techniques using comparisons with modern analogues to explain the ancient record. A large suite of facies models has now been developed which conceptualize our understanding of depositional processes and their sedimentary results.

On a larger scale, application of facies model studies to an entire basin yields information on regional depositional systems. By employing regional seismic stratigraphic studies and various techniques of basin mapping (e.g., lithofacies mapping, paleocurrent measurements and geophysical well log analysis), sedimentologists now carry out a procedure of genetic stratigraphic analysis. Sedimentological data are correlated with biostratigraphic and other conventional stratigraphic information, in a continued iterative process, to find the "best fit". These new techniques of basin analysis have yielded results of profound importance for the exploitation of the various fuel and mineral resources hosted in sedimentary rocks. This is particularly true in the case of petroleum exploration.

Sediments accumulate under a wide variety of depositional environments. For most of these, studies of modern sedimentary processes and products, together with recognition of ancient analogues in the sedimentary record, have provided a broad base of data and ideas with which to carry out sophisticated basin studies. There remains an outstanding exception to this: the sedimentology of glacial depositional environments, which remain very poorly understood.

The economic importance of glacial sediments and rocks, however, is of considerable significance. With regard to the Canadian economy, mineral exploration in glaciated terrains, onshore and offshore geotechnical engineering, waste management and water resource management all require a firm understanding of glacial sediments and their distribution across Quaternary glaciated basins. Elsewhere, in Oman and Australia, significant hydrocarbon resources are located within glacial reservoirs of Permo-Carboniferous age. The Miocene to Holocene Yakataga Formation of the Gulf of Alaska, a glaciomarine complex with a cumulative thickness of nearly 5 km, also can be mentioned as a petroleum-hosting glacial succession.

Because of the economic importance of these and other glacial rocks and the need for a wide range of studies to bring our knowledge of glacial depositional systems up to a standard comparable to that of, for instance, fluvial sediments, reefs or submarine fans, a major multifaceted research program is being undertaken at the University of Toronto by the Glaciated Basin Research Group.

This report is a brief review of the Group's local work in southern Ontario, which is concerned with reconstructing the infill of a major glaciated basin (the Laurentian Channel) using modern methods of basin analysis. This work is providing a significant stimulus to the study of Pre-Quaternary glaciated basins elsewhere. The principles and practice of glaciated basin analysis shown here can be applied elsewhere in Canadian glaciated terrains both onshore and offshore, and will be of interest to the wider geoscience community.

The Laurentian Channel: Definition and Physical Setting

The Lake Ontario Basin, occupied by one of the five Great Lakes, has long attracted the attention of glacial geologists because of the exposure of sediments from the penultimate glaciation (Illinoian) and last interglacial (Sangamon) at the Don Valley Brickyard in the eastern suburbs of Toronto (Fig. 1). These old sediments are blan-

Figure 1 *Don Valley Brickyard; exposure of last interglacial lacustrine facies (Don Formation). For location see Figure 3. The formation can be identified on geophysical well logs as a lower coarse-grained fluvial unit (Fig. 5) and is preserved, with perhaps older sediments, in bedrock depressions below Scarborough Formation delta (e.g., holes 4-74 to 13958; Figs. 3, 8). Their investigation is of great significance given the imminent closure of the Don Valley Brickyard (Eyles, 1984)*

keted by a thick last glaciation (Wisconsin) sequence that has been described as one of the most complete records in North America, and which is spectacularly exposed east of Toronto along the Scarborough Bluffs (Fig. 2).

The glacial and interglacial sequences of the Toronto area fill a broad bedrock basin, trending north-south, that connects Lake Ontario to Georgian Bay. Contours of bedrock elevation (Fig. 3) show a major buried valley system, trending southeast from Georgian Bay to the Metropolitan Toronto area, parallel to the strike of upper Ordovican shales and the Niagara Escarpment which defines the bedrock basin to the west (Fig. 3). This complex basin is that identified by J.W.W. Spencer (1890) as the precursor to the modern St. Lawrence River which, as the "Laurentian River", flowed directly across the Ontario peninsula from Collingwood to Toronto. The route is of unknown age, but it is part of a relict regional drainage system that predates the modern Great Lake drainage network in the mid-continent region.

The basin has been severely modified by glacial erosion to give an overdeepened, "up and down" long profile that reaches sea level at its deepest point. This characteristic long profile is typical of glacially-influenced bedrock valleys. The effects of such erosion were even more profound where deep re-entrants were cut in the Niagara Escarpment (Fig. 3), comparable to those occupied by the finger lakes of adjacent Upper New York State (Straw, 1968). The Laurentian Channel is of major significance to reconstruction of Quaternary paleoenvironments, as it contains sediment thicknesses of up to 250 m with the strong likelihood that basal sediments were deposited prior to the oldest Illinoian sediments exposed at Toronto. In addition, the channel fill contains a number of different aquifer systems and therefore represents a major water resource.

Figure 2 *Scarborough Bluffs, some 10 km long and over 100 m high, looking west to the city skyline of Toronto. An upper glacial complex is draped over the Scarborough Formation delta (Figs. 5, 6). The top of the delta lies at 120 m.a.s.l. some 45 m above the level of Lake Ontario (Figs. 7, 8, 9). Bedrock topography shown in Figure 3b*

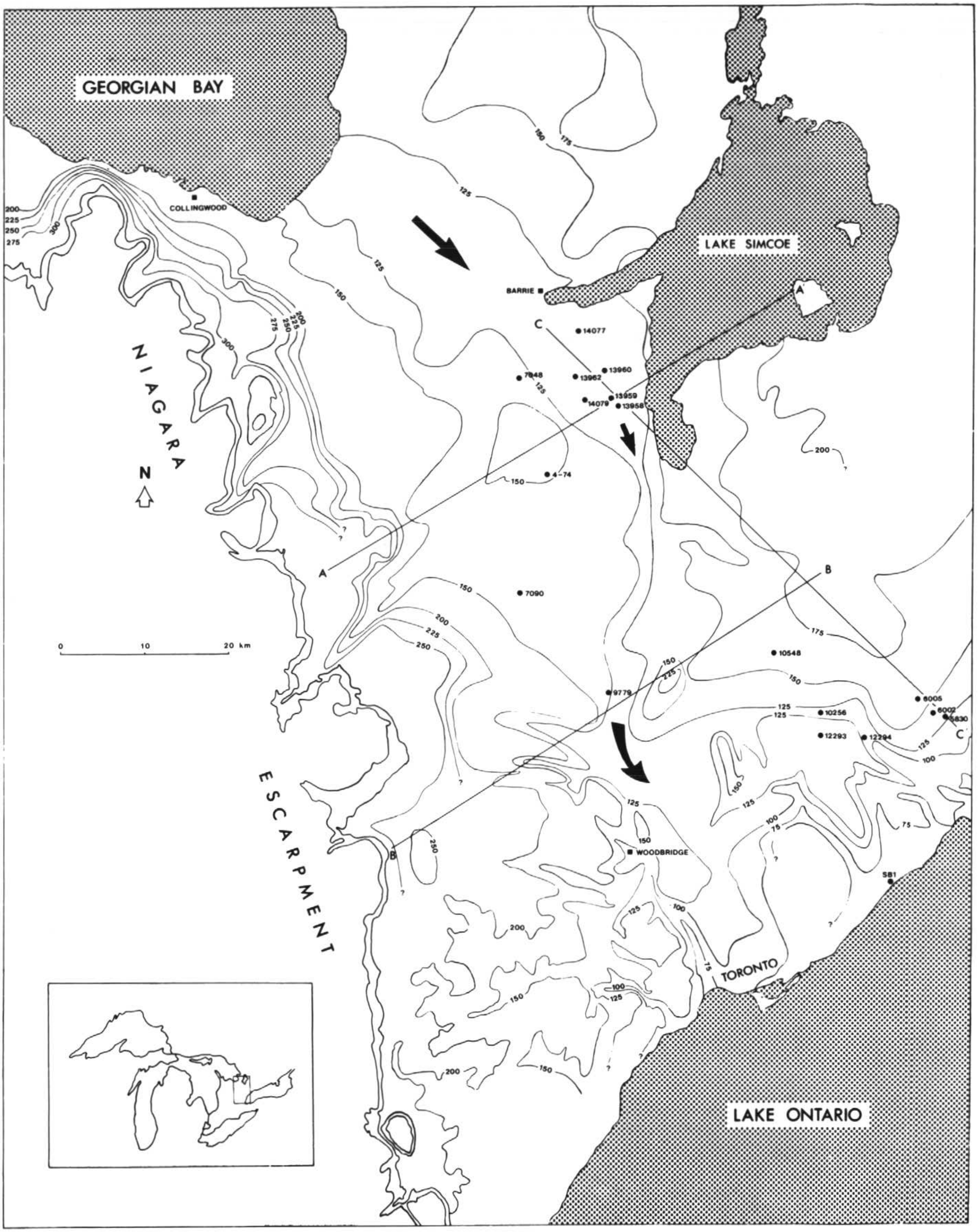
Surface and Subsurface Facies Mapping

The geophysical well log, long used by petroleum geologists to identify and map subsurface facies and associated "depositional systems", is being employed to detail the glacial sedimentary infill of the Laurentian Channel. Geophysical well logging has been used by the Water Resources Branch of the Ontario Ministry of Environment to identify major aquifers, and a number of published and unpublished well logs are available from the Ministry and from industry sources (e.g., Sibul *et al.*, 1977; Fligg, 1983; Fligg and Rodriques, 1983) which are sufficient to allow a first attempt at reconstructing the subsurface architecture along the basin. A major problem in the early stages of the investigation was the identification of sediment facies from the well log data, given only brief and highly inaccurate drillers' descriptions of the lithologies being logged. Drillers' logs that report "muddy sand-gravel" are common. The desire to obtain a better picture of the subsurface geology prompted the drilling of a 104 m-deep test hole to bedrock along the highest part of the Scarborough Bluffs along the northern shore of Lake Ontario (Fig. 4). The 6-inch diameter hole was sited immediately adjacent to the bluff face at Cathedral Bluffs, which had been logged previously employing sedimentological logging techniques (Fig. 5). Thus, a highly detailed record of sedimentary structures, bed contacts and lithologies was available with which to compare details of the geophysical well logs. This reference hole was then used as a key to the interpretation and correlation of other geophysical well logs along the Laurentian Channel.

A number of geophysical logging techniques are available for subsurface facies modelling (e.g., caliper, density, sonic, spontaneous potential, gamma, single-point resistance and neutron probes; see Merkel, 1981 and Cant, 1983 for useful review). Space does not permit a full description of each, and the application of these techniques to glacial sediments will be described elsewhere. Figure 5 shows single-point resistance and spontaneous potential logs alongside a vertical profile constructed from field lithofacies logging. The single-point geophysical log measures the resistance between a surface electrode and an electrode tool lowered down the hole. An increase in grain-size results in increased values of resistance, and is shown by a deflection of the well log to the right (Fig. 5). The single-point tool has a restricted radius of investigation (approx. 25 cm) and, consequently, is very useful for identifying detailed changes in resistivity generated by finely interbedded lithofacies. The spontaneous-potential tool measures naturally occurring potentials in the sediment; finer grained, more muddy lithofacies generally will exhibit higher potentials. The very close correlation between geophysical well log characteristics and a detailed lithological log from the Scarborough Bluffs is shown on Figure 5.

The Stratigraphy at Scarborough Bluffs; A Window into the Infill of the Laurentian Channel

The succession along Scarborough Bluffs, at the southern end of the Laurentian River Basin, is composed essentially of a lowermost delta body (the Scarborough Formation; Karrow, 1967) draped by a glacial complex of diamicts (pebbly muds) and intervening deltaic lithofacies (Figs. 5, 6). A lower prodelta member of the Scarborough Formation delta, about 30 m thick, is composed of laminated silts and clays with many graded and small scale cross-laminated fine-sand units. This is reflected in a serrated geophysical well log response. The coarsest part of the delta, marked by an abrupt response on the well logs (Fig. 5), is associated with large (1 m) planar and trough cross-bedded sands sitting within broad shallow channels, indicating a southerly paleo-flow direction (Fig. 7). Small trough fills of rippled sands and mud drapes give rise to the fining upward trend shown by the resistivity log at the top of the delta. These troughs contain thick lenses of detrital peats and are associated across the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6005
6002
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12293
12294
581
WOODBRIDGE
TORONTO
LAKE ONTARIO
75
100
125
150
175
200
225
250
275
300

◁ **Figure 3 a)** *Generalized bedrock contours along Laurentian Channel. Location of geophysical well logs and geophysical calibration hole at Scarborough Bluffs also shown. Transects (A-A', etc.) are locations of sections shown in Figure 8. Arrows identify axis of Laurentian Channel.* **Figure 3 b)** *Bedrock topography showing complex channel system within southeastern sector of Laurentian Channel north of Scarborough Bluffs shoreline. Overlying sediments are shown in Figure 6b. Bedrock elevation data from Haefeli (1970), Lewis and Sly (1971), Sibul* et al., *(1977) and recent water well records of Ontario Ministry of Environment*

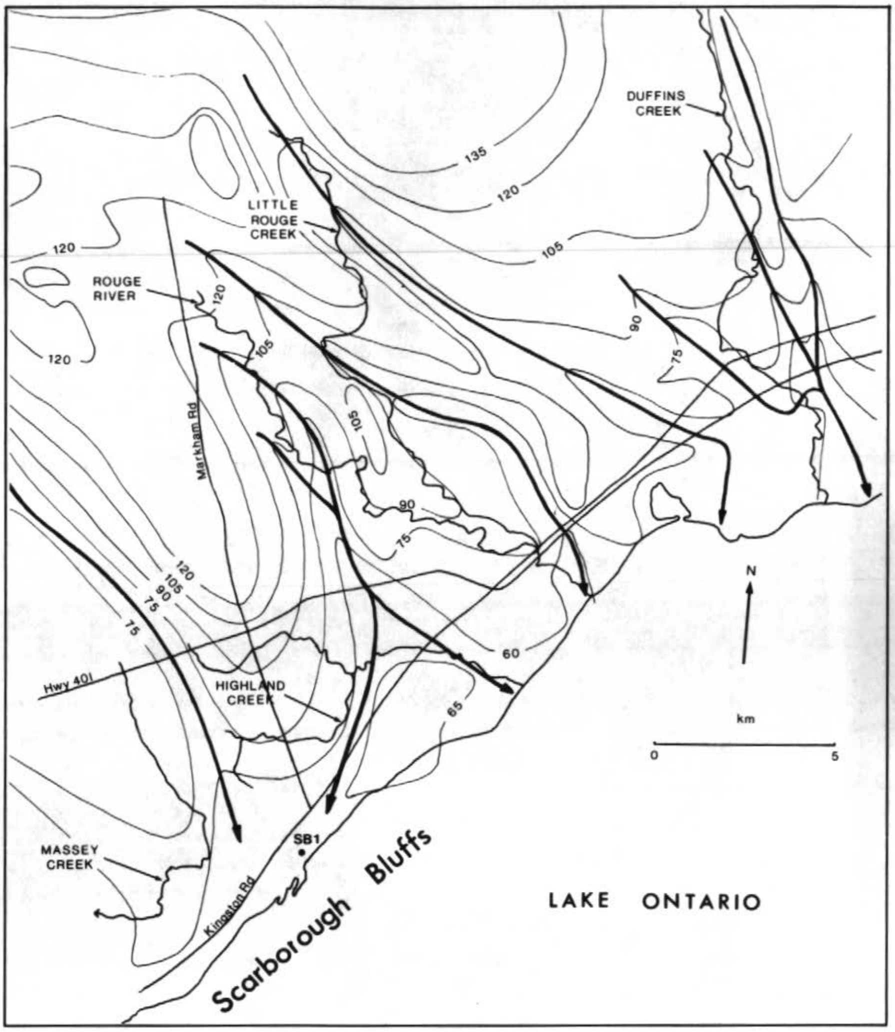

Figure 4 *Location of 104 m geophysical calibration hole SB-1 (drill rig in postion) at Cathedral Bluffs Ravine, Scarborough Bluffs. The hole is adjacent to section 0651 logged in detail by Eyles and Eyles (1983; Fig. 5). The magnetostratigraphy of the section is described by Eyles et al. (1983b). The base of the Sunnybrook, Seminary and Meadowcliffe diamict assemblages in arrowed (2, 3, resp.). The upper prograding sand of the underlying Scarborough Formation (Fig. 5) can be seen clearly below the Sunnybrook (see also Fig. 7)*

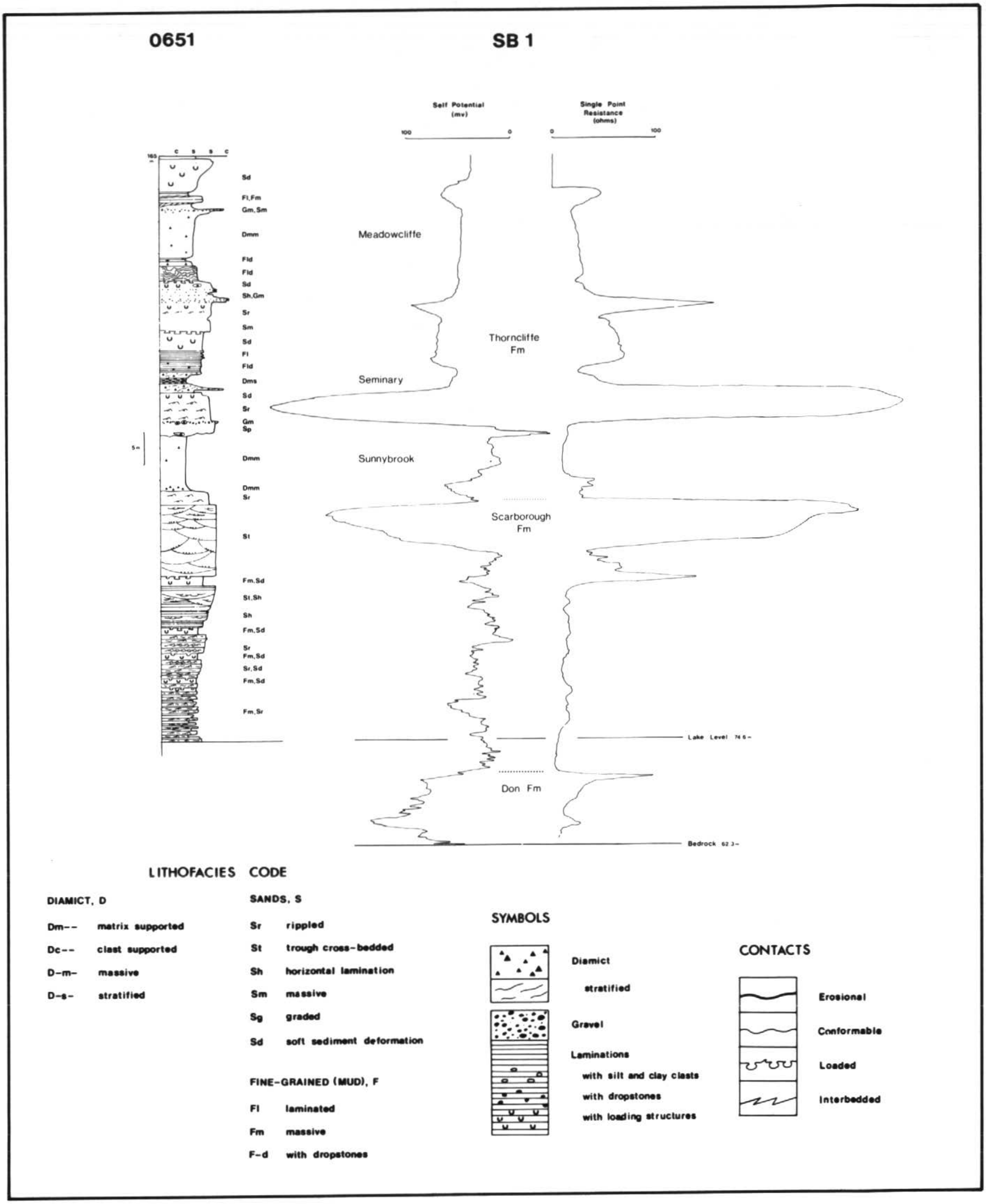

Figure 5 *Geophysical well logs and lithofacies log from Cathedral Bluffs. Lithofacies codes from Eyles* et al. *(1983). Interglacial Don Formation is overlain by coarsening upwards Scarborough Formation delta. The delta is blanketed by a thick glaciolacustrine complex of Sunnybrook, Seminary and Meadowcliffe diamict assemblages separated by laminated silty clays (prodelta turbidites; Figure 6a) and deltaic sands. Lithofacies log from Scarborough Formation is generalized from Kelly (1982). The entire stratigraphy is overlain erosively, by the Halton Till (Karrow, 1974) a widespread lodgement till unit deposited below a regionally extensive Late Wisconsin ice sheet*

Metropolitan Toronto region with significant showings of methane gas in water wells. This gas continues to be employed as a local domestic and industrial energy source but also poses problems with regard to unforeseen gas buildups in well casings.

The delta top is at some 35 m above the modern lake level at Scarborough (Figs. 5, 6). Several abandoned channels up to 100 m deep and 1 km broad are cut into the delta top (Fig. 6) and are infilled by a fine-grained diamict (pebbly-mud) that has a drape-like geometry (the Sunnybrook diamict; Fig. 6). The Sunnybrook diamict is overlain by sandy deltaic lithofacies (the Thorncliffe Formation; Fig. 4) which also includes two more diamict units (the Seminary and Meadowcliffe). Diamicts generally have a silty-clay matrix and exhibit few clasts; their description in the field has been facilitated by the use of a simple lithofacies code scheme that relates matrix/clast relationships and internal structures to a mnemonic letter series. This not only avoids the use of genetic terms of uncertain or disputed meaning, e.g., "till" (Dremanis, 1984; Eyles *et al.*, 1983, 1984), but also allows detailed lithofacies descriptions.

Detailed sedimentological logging of diamicts has identified considerable lithofacies variation within individual units. Massive lithofacies occur in association with stratified units that show evidence of traction current activity in the form of current-bedded sand stringers and interbeds, and downslope resedimentation, as evidenced by fold noses, flow banding and soft-sediment brecciation. In addition to identifying lithofacies variability, particular regard is paid also to the nature of lithofacies with which diamicts are associated (i.e., sequence context) as an aid to interpretation of diamict genesis (Eyles and Miall, 1984; Walker, 1984). A crucial part of this process is the detailed description of basal and upper diamict contacts with associated lithofacies. Basal contacts between diamict and underlying deltaic facies along the Scarborough Bluffs are conformable, interbedded and frequently transitional, demonstrating continuity of deposition. The diamicts are overlain by lensate basins of laminated and graded silty clays, deposited by turbidity currents (Fig. 6a). These laminations coarsen upwards into sandy lithofacies, indicating delta progradation. The most common deltaic lithofacies is a massive, sometimes crudely-bedded silty sand with abundant dish- and water-escape structures, indicating rapid subaqueous sedimentation. These show many similarities with facies of subaqueous glacial outwash in the Ottawa Valley described by Rust (1977) and Cheel and Rust (1982).

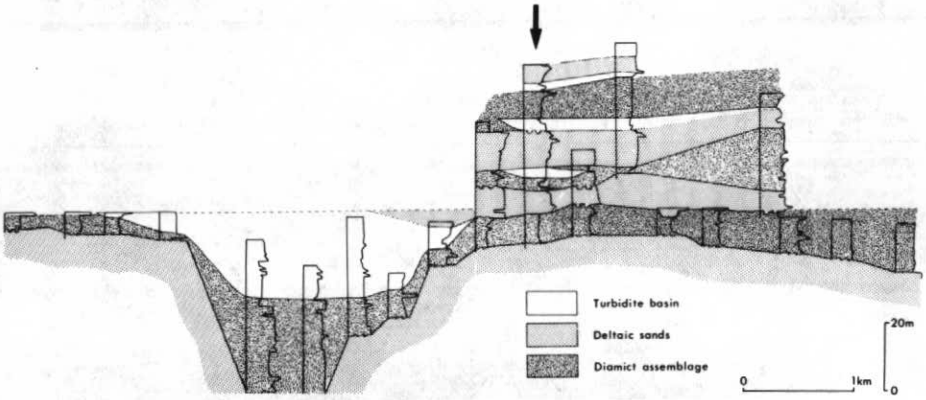

Figure 6 a) *Lithofacies associations exposed at Scarborough Bluffs. Note channels on surface of Scarborough Formation delta and associated thickening of lowermost diamict assemblage (Sunnybrook). Both the delta and overlying diamict can be traced northwards along the Laurentian Channel (Fig. 8). Position of geophysical calibration hole SB-1 and lithofacies log 0651 (Fig. 5) are shown as arrowed line.*

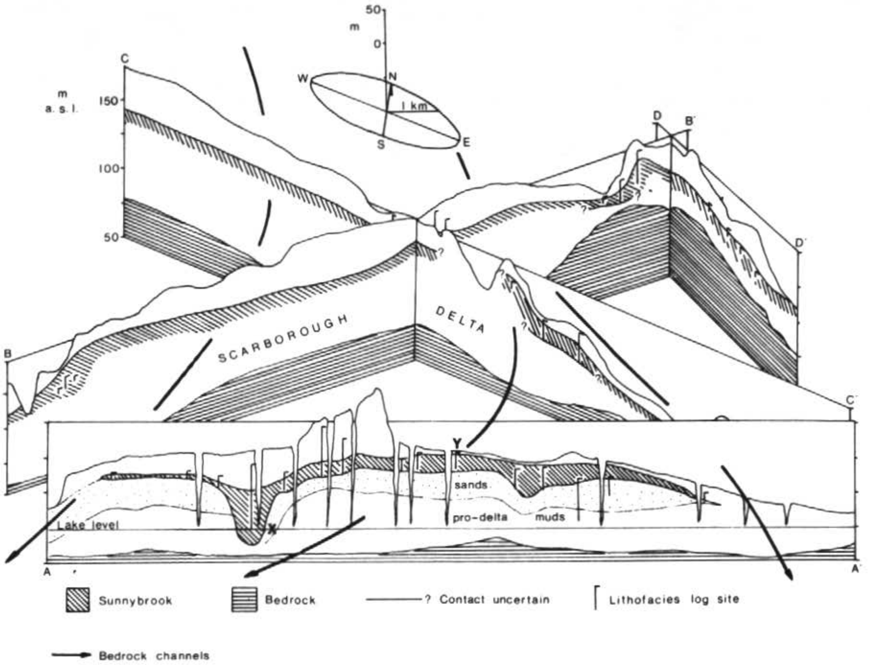

Figure 6 b) *Transects showing geometry of Sunnybrook diamict assemblage as a drape over the Scarborough Formation delta surface. Heavy arrowed lines mark trend of bedrock valleys (Fig. 3). Note thickening of Sunnybrook in abandoned fluvial channels on delta top. The marina shown on Fig. 2 is located at X. Figure 7 was taken looking eastward from Y*

This exercise in identifying the sequence context of the three diamict units exposed along the Scarborough Bluffs establishes continuity of deposition between episodes of diamict accumulation and subaqueous deltaic sedimentation. Furthermore, the lack of evidence for the movement of an ice sheet base in the form of glaciotectonic structures in sediments that underlie the diamicts, coupled with a distinct, planar drape-like diamict geometry, indicates that the diamicts were not deposited directly by grounded glaciers. These fine-grained diamicts can be identified as having originated on a muddy, glacial lake floor under a depositional regime of ice-rafting and fine-grained pelagic sedimentation (Eyles and Eyles, 1983, 1984).

The same diamict lithofacies are reported from many other glaciolacustrine and marine basins (Miller, 1953; Ferrians, 1963; Miller, 1973; Armstrong, 1981; Quigley, 1983; Domack, 1983; Elverhoi *et al.*, 1983). Along the Scarborough Bluffs the complex range of massive and stratified diamict lithofacies within each diamict unit records the activity of variable bottom currents, downslope mass movement of diamicts over the basin floor and variation in the nature and volume of suspended sediment deposition and ice rafting. Resedimented lithofacies are most common in the lowermost diamict (the Sunnybrook), in response to the irregular relief of the underlying delta top. Because each diamict exhibits many different internal lithofacies, the term "diamict assemblage" is used.

The controls on deposition of the three glaciolacustrine diamict assemblages and intervening deltaic sediments at Scarborough are likely to have been complex. The change from diamict accumulation to deltaic sedimentation may be caused by many factors, such as changes in water depths as a result of vertical basin movements in response to isostatic loading by sediment, water and ice sheets. Other factors that may be involved are glacier damming of the lake outlet and changes in sediment supply. Previous workers have sought to interpret the succession in terms of a simple model involving the repeated advance and retreat of a grounded ice sheet. In this scheme diamicts were described as basal deposits of grounded ice ("till"), separated by lacustrine sediments deposited in interstadial lakes that formed after ice retreat. Instead, the picture emerging after detailed sedimentological study is that the succession of diamicts and deltaic lithofacies is a single, albeit complex, glaciolacustrine sequence.

Subsurface Well Log Correlations Along the Laurentian River Basin

Figure 6 shows the distinctive stratiform and conformable geometry of deltaic and diamict lithofacies along Scarborough Bluffs. Comparison of the geophysical well log characteristics of this sedimentary sequence with those available from other sites along the Laurentian Channel can be used to reconstruct the subsurface stratigraphy along the channel. During the course of a regional study of groundwater potential, Fligg (1983) recognized a prominent subsurface geophysical marker horizon in the area around Barrie, which he interpreted as a coarsening-upwards glaciolacustrine unit; no correlations were attempted to the south. Comparison of the geophysical logs from the test hole at Scarborough with other local geophysical data enables the Scarborough Formation delta and overlying Sunnybrook diamict assemblage to be correlated with the data of Fligg (1983) to the north. The coarsening-upwards log from the Scarborough Formation and the abrupt "box-like" deflection in resistivity associated with the overlying fine-grained Sunnybrook diamict assemblage appears to be a highly distinctive geophysical marker along the Laurentian Channel from Barrie, in the north, to Scarborough Bluffs.

The elevation of the top of the Scarborough Formation in the northern part of the channel at Barrie lies between 180 and 190 m.a.s.l. with no change in elevation across the channel (Fig. 8). A distinct southward slope can, however, be identified (Fig. 9), and the top of the Scarborough Formation lies at 120 m elevation some 80 km to the south at Scarborough. There is a marked steepening of this surface south of the 170 m contour and it is possible that this break in slope divides the subaerial delta plain to the north from the subaqueous front sloping to the south. The thickness of the Scarborough Formation near Lake Simcoe averages about 25 m, thickening to 60 m at Scarborough Bluffs. This may reflect enhanced accumulation on the delta slope in deeper water of the Lake Ontario Basin and/or thinning over bedrock highs inland.

The glaciolacustrine Sunnybrook diamict assemblage appears to rest conformably on the surface of the Scarborough Formation along the channel, with no evidence of a major regional unconformity between the two that is typically associated with deposition from grounded ice sheets. The two uppermost diamicts (Seminary, Meadowcliffe) are known, from mapping, to pinch-out inland within a few kilometres of the Bluffs (Kar-

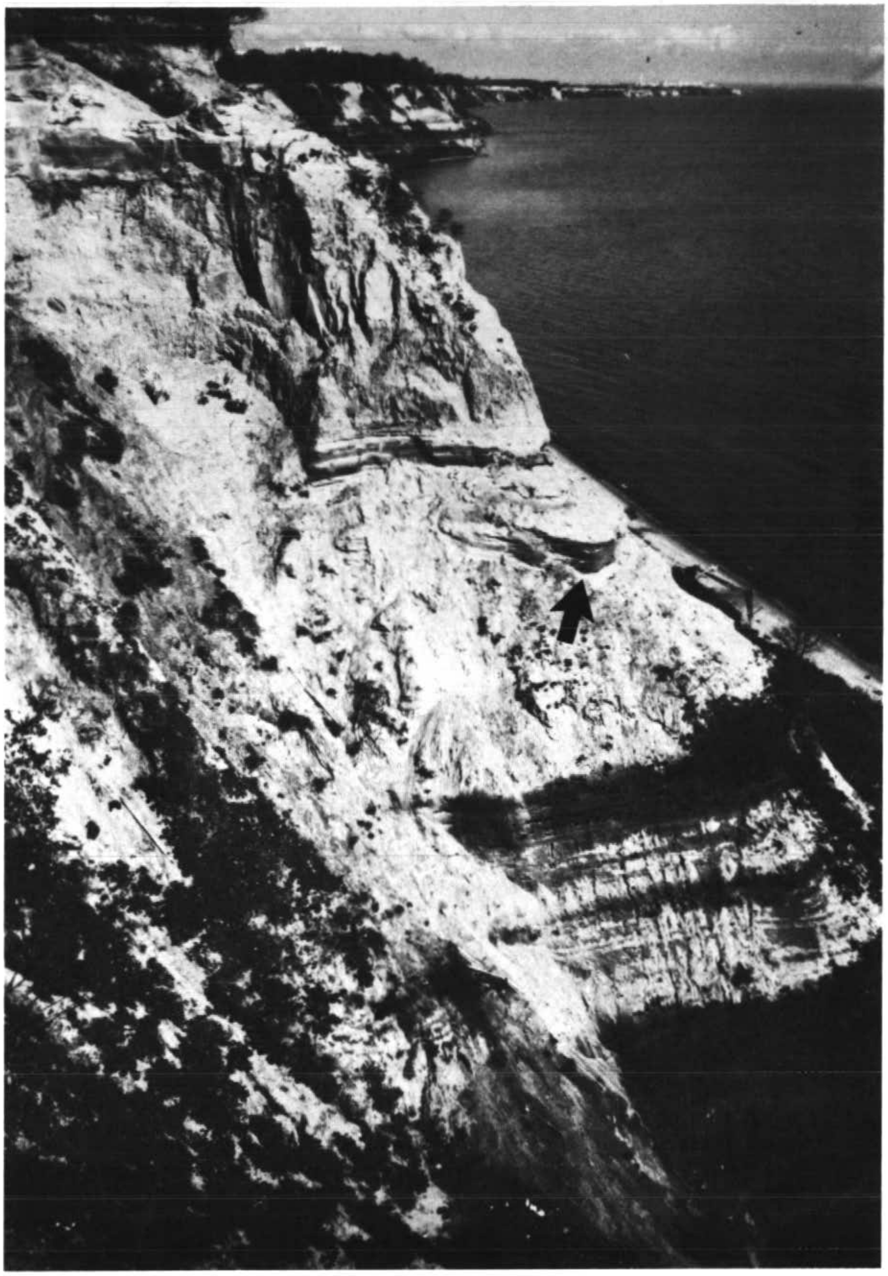

Figure 7 *Top of Scarborough Formation delta below glaciolacustrine diamict (Sunnybrook) at Sylvan Park (Section 259†; Eyles and Eyles, 1983). Channels with planar and trough cross beeding and detrital peat blankets are arrowed. Paleoflow directions are southerly to Lake Ontario Basin*

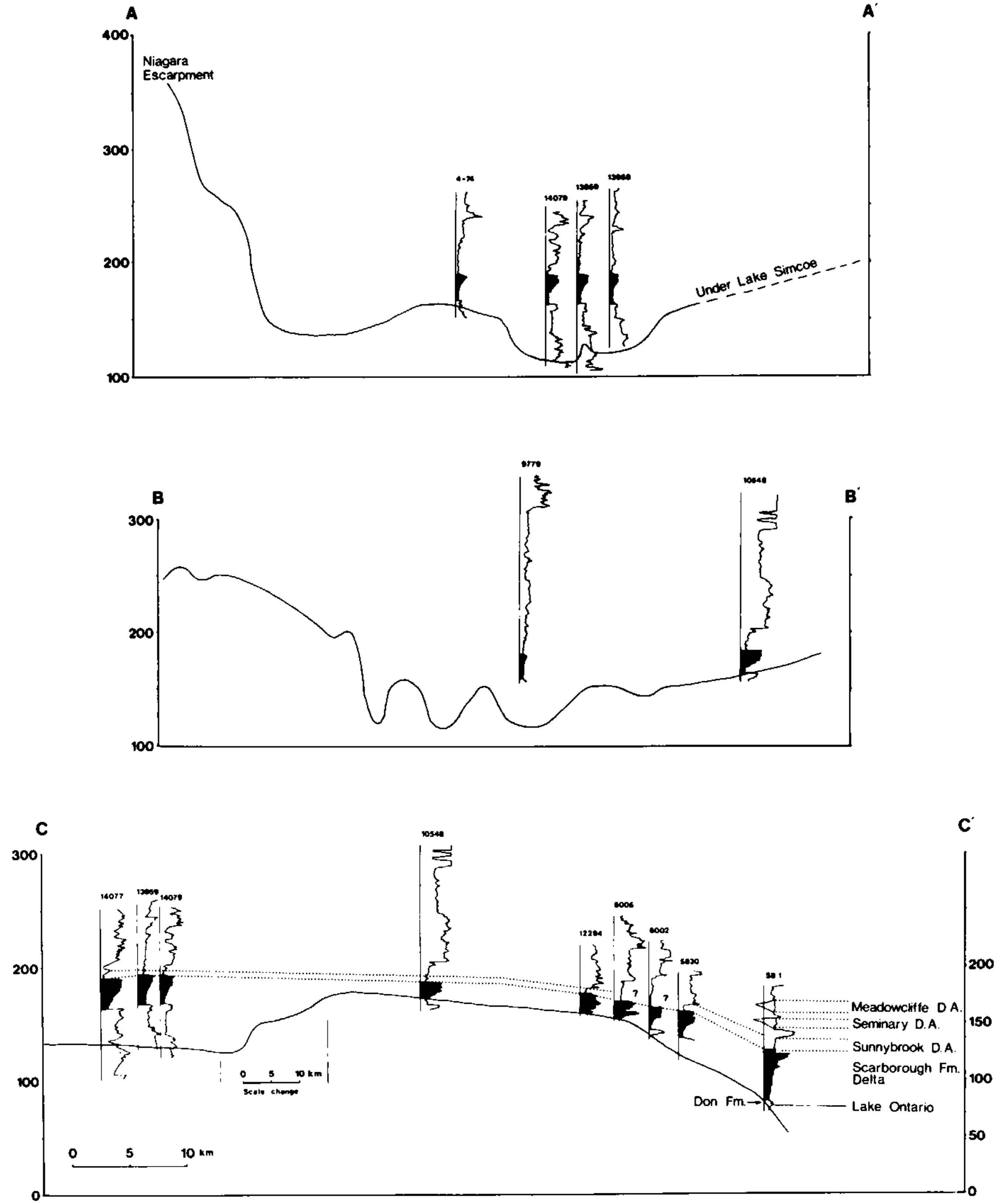

Figure 8 *Subsurface well log correlations of glaciolacustrine units along and across the Laurentian Channel. A coarsening-upwards Scarborough Formation delta body and overlying fine-grained glaciolacustrine diamict assemblage (Sunnybrook; Figures 5, 6) forms a distinct marker horizon. For location of well logs see Figure 3. The Meadowcliffe and Seminary diamict assemblages pinch-out inland with the deltaic sands of the Thorncliffe Formation (Figure 5) which is truncated by varying thickness of grounded ice facies. Geophysical well log data from Fligg (1983) and Sibul* et al. *(1977). Elevations in metres above sea level*

row, 1967); deltaic sediments that separate the two diamicts along the Bluffs merge inland as a thick, upper deltaic complex seen as a coarsening-upward geophysical well log signature on many well logs (Fig. 8). Figure 8 strongly suggests that these two diamicts may simply record deeper water, fine-grained sedimentation offshore in the Ontario Basin, but more data are needed to confirm this. The existence of a major, high level lake body ponded to an elevation of a least 190 m above sea level some 115 m above the modern lake level is clearly indicated.

There are unfortunately few geophysical well logs for the western side of the Laurentian Channel, especially below Metropolitan Toronto. We are currently extending our analysis in these areas by reference to construction records; despite the problems noted above with drillers' logs, the identification of a regionally extensive Scarborough Formation delta top and a northward slope from 120 m.a.s.l. at Lake Ontario is proving very valuable as a key to subsurface records.

Throughout the channel, deposits of the Late Wisconsin, deposited after about 20,000 y.b.p. (Karrow, 1974; Dreimanis, 1977), rest with a marked unconformity on the older glaciolacustrine sequences. The Late Wisconsin sediments were deposited by a grounded ice sheet, and thus are dominanted by coarse-grained lodgement tills and outwash. The Oak Ridges Moraine, widely reported as an interlobate moraine ridge formed between Late Wisconsin ice lobes, can be seen to rest on the underlying glaciolacustrine fill of the Laurentian Channel (Fig. 9).

Figure 8 shows coarse-grained, probably fluvial, sequences below the Scarborough Formation, preserved between bedrock highs inland along the Laurentian Channel. At Scarborough the same stratigraphic position is occupied by the Don Formation (Fig. 1), with a rich warm-temperate flora and fauna from the Sangamon Interglacial. Clearly, a drilling and coring program along the Laurentian Channel in the area of hole 14079 (Fig. 8) would add significant data to our knowledge of the last interglacial and perhaps even older environments.

Implications for the Late-Pleistocene Glacial Record in Ontario and Surrounding Great Lakes Basins

Inherent in the application of basin analysis concepts to the study of the sedimentary infills of glaciated basins is a radical reappraisal of many formal stratigraphic notions. A longstanding, and commonly abused foundation of formal stratigraphy is the identification of reference stratigraphies (type sections) which are used for interregional correlations. In many areas these reference stratigraphies are defined solely on the basis of crude lithological and petrographic descriptions and are correlated from area to area by simple "count from the top" schemes. In this way, the vertical succession of lithologies at any one type site is held to define the environmental history of the entire region. The Scarborough Bluffs stratigraphy below the overlying Late Wisconsin sediments (Fig. 5) is considered as a reference section for the long Early and Middle Wisconsin time interval, postdating deposition of the Interglacial Don Formation (Dreimanis, 1977; Karrow, 1984). The vertical sequence of diamicts and deltaic sediments has been interpreted to record the regional advance and retreat of grounded ice margins. This sequence has been widely correlated, as a scheme of stadials and interstadials having implicit climatic connotations, across mid-continent North America and the Great Lakes Basins (Dreimanis and Karrow, 1972; Karrow, 1984).

The Scarborough Bluffs stratigraphy is now recognized as the complex fill of a large lacustrine basin, and its lithological record cannot be extrapolated in traditional "type section" fashion to other areas outside the basin (Ford *et al.*, 1984). This can be clearly demonstrated with reference to the Seminary and Meadowcliffe diamict assemblages which are of restricted extent and appear to be fine-grained lateral facies equivalents of sandy deltaic lithofacies inland (Fig. 8). Their distribution does not reflect simple movements of grounded ice margins, but depends on a variety of environmental controls. Lithological changes within complex glaciolacustrine sequences may be controlled by changing water depths in response to basin subsidence caused by ice sheet, water and sediment loading, local and regional hydrodynamics, location of meltwater inputs, current regimes, basin relief and configuration of ice margins. Many other controls can be identified. Future emphasis in the description and interpretation of Quaternary stratigraphies should be directed not to the proliferation of "type sites", but to detailed documentation and analysis of local facies sequences and their continuity and variability across the sedimentary basin. This approach is fundamental to a better understanding of Late Pleistocene sedimentary environments and depositional histories of glaciated basins.

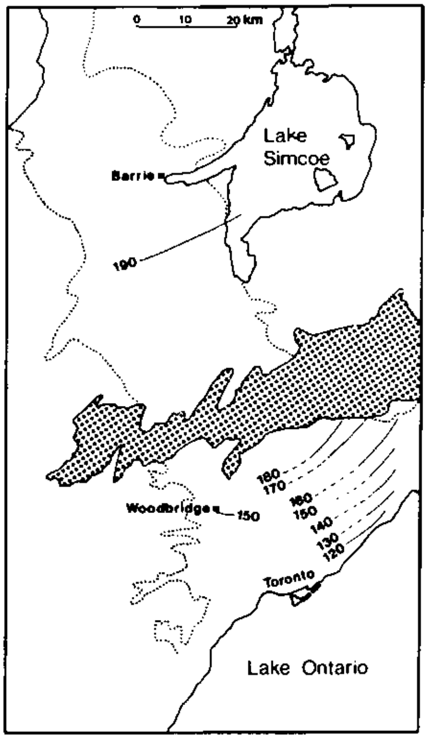

Figure 9 *Regional slope of upper surface of Scarborough Formation delta reconstructed from Figure 8. The increase in slope south of the 170 m elevation contour may distinguish the delta top of the north from delta front towards the Lake Ontario Basin. Dotted line is the 150 m bedrock contour defining the trend of the Laurentian Channel. All elevations are corrected for postglacial differential uplift (i.e., tilting) using the data of Deane (1950) and Fligg (1983). The area depicted by dots is the Late Wisconsin Oak Ridges Moraine*

Application to Pre-Quaternary and Applied Investigations

The purpose of reconstructing the internal stratigraphic architecture of the Laurentian Channel connecting Georgian Bay and Lake Ontario is primarily one of establishing large-scale facies models for glaciolacustrine sedimentation. Current glaciolacustrine facies models address sedimentation in relatively small basins in mountainous areas that are subject to strongly seasonal patterns of deposition; relatively little is known of deposition in extensive basins ponded on low relief mid-continent areas and "plumbed in" to the subglacial drainage systems of a continental ice sheet. These glaciolacustrine giants are so large that they are best considered in the context of marine sedimentation. Their study is important because they are well represented in the rock record (see below), and because modern day analogues of the same scale do not exist. It should be noted that Program 219 of the International Geological Correlation Project, titled "Comparative Lacustrine Sedimentology in Time and Space" has been announced recently (February 1984). The aim of defining typical facies distributions in large lake basins of different geological ages and tectonic settings should be a major stimulus to research into glaciolacustrine "giants".

The field and subsurface techniques utilized in this report may have widespread application in other Quaternary glaciated terrains of North America where extensive lake basins formed during ice sheet incursions and retreat (e.g., Lake Agassiz, Copper River Basin, Lake Barlow – Ojibway and other Great Lake Basins). Comprehensive studies of basins in these and other areas would provide a significant aid to interpretation of the infills of trough-like intracratonic basins of strikingly similar dimensions, dating from the Permo-Carboniferous glaciation of the Gondwana Supercontinent. The basins are associated with significant petroleum resources in reservoirs that are as yet poorly understood. In this case, comparative data between large Quaternary lake basins and the older hydrocarbon-bearing basins offers significant insights into the internal architecture of reservoir rocks and the nature of stratigraphic trapping mechanisms. It is likely that many reported multiple tillite and outwash stratigraphies are of a similar origin to the glaciolacustrine facies reported by us from Ontario. Their stratigraphy reflects very complex responses to basin subsidence, water levels and ice volumes, and not simple climatically-controlled ice advance/retreat cycles.

Current research at Toronto is focused on identifying different criteria that can be employed to discriminate diamicts deposited subaqueously in lacustrine or marine basins from those deposited at the base of grounded ice sheets. Facies techniques provide powerful criteria and rely on identifying the nature of associated lithofacies, the relationship of diamicts to these facies (interbedded, transitional, erosive, etc.) and the geometry of the diamict sequence (planar, lensate, etc.) across the sedimentary basin. These techniques rely on good exposure or subsurface well data. These are not always available and considerable attention is being devoted to paleomagnetic means of identifying different diamict types. Paleomagnetic techniques require only small samples from core or restricted outcrop, and depend on identifying grounded ice facies by recognizing remanence patterns that have been disturbed by shear at the ice base. Characteristic distensions around magnetic pole positions can be identified. In contrast, remanence patterns from subaqueous diamicts formed by suspension deposition and ice-rafting have a remanence that is undisturbed by shear processes and which show tight clustering around pole positions (Day and Eyles, 1984). Another useful magnetic technique is the measurement of the anisotropy of susceptibility. This provides a rapid indicator of the orientation of sedimentary particles; again, different *microfabrics* can be identified for diamicts of contrasting genesis. These magnetic techniques have considerable potential application in glaciated terrains with regard to mineral exploration, where it is critical to isolate diamicts deposited below ice sheets from those formed subaqueously. This is because any geochemical anomaly or mineralized float within subaqueous diamicts cannot be related in a simple fashion to source, as can be done with dispersal fans and where ice flow directions can be deduced from grounded ice facies. New drilling techniques (e.g., resonant drilling) that produce a high quality core offer the possibility in the long term of rapid paleomagnetic determination of the genesis of diamicts in the subsurface. Such work is a valuable supplement to the facies techniques outlined above.

In offshore marine environments, the ability to differentiate grounded ice deposits from other subaqueous diamicts is of considerable engineering significance. The former facies are overconsolidated and provide good foundations for offshore structures, but subaqueously deposited diamicts are variably consolidated and frequently display *soft zones* at depth. These soft zones result from excess porewater pressures developed during rapid deposition, coupled with an inability to drain freely, and are a threat to the stability of large foundation structures constructed for oil and gas production."Jack-up rigs" are particularly at risk. In this case, identification of diamict origin offers valuable predictive data for geotechnical prediction.

The basin analysis techniques demonstrated here are especially pertinent to problems of groundwater resource exploration and management in glaciated terrains. Classically, resource studies of this kind rely on a high density of investigation and production wells to locate and define local aquifers. In contrast, an integrated, subsurface mapping approach permits aquifers to be related to a basinal context and provides the framework necessary for establishing groundwater flow behaviour on a regional scale. This understanding is essential for effective management of existing groundwater resources and for evaluating resource potential in unexplored, underdeveloped regions. For example, in the Laurentian Channel the regional association and correlation of locally defined aquifer systems is currently being undertaken by combining the basin analysis approach with regional investigations of major and minor ion groundwater chemistry. The results of this geochemical work show that sands of the Scarborough Formation deltaic sequence form a major aquifer throughout the region, indicating a regional flow system connecting Georgian Bay and Lake Ontario.

Future Prospects

In this article an approach to the study of glacial sediments and basins has been identified based on techniques developed some time ago in the petroleum industry, but which have not been systematically employed by glacial geologists. These basin analyses rely on very detailed facies descriptions and analyses from available outcrop or core data coupled with basin-wide investigations using downhole geophysical well loggings, paleoecological, age and other data. Ironically, at a time of rapidly increasing urbanization in Ontario, with major environmental pressures being placed on subsurface sediments in connection with water resource management, contaminant migration, aquifer thermal energy storage and waste control programs, no government or industry organization has either the mandate or the capability to carry out subsurface basin investigations of this type – yet the costs of basin-wide drilling programs are beyond even multidisciplinary groups of university researchers. Clearly, the future of sophisticated basin modelling, with attendant spin-off for analyses of pre-Quaternary glacial basins and other applied investigations, lies in closer cooperation between university, industry and government over the siting, drilling and subsequent logging of drill holes and core material. If proprietory restrictions can be overcome, such a scheme would maximize the benefits of subsurface studies across the geoscience community.

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