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Articles

Applied Sedimentology in an Urban Environment — the Case of Scarborough Bluffs, Ontario; Canada's Most Intractable Erosion Problem

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Introduction

The desire for a residence with a view, whether for protection, social position or aesthetics, has from time immemorial resulted in direct collision with the forces of Nature. Examples abound where the best piece of local real estate often turns out, sooner or later, to be where all the geological action happens. Memories are also short and the lessons of major disasters are soon ignored. Along the many thousands of kilometres of lakeshore around the Great Lakes Basins, the desire for a lakeward view is exacting a major toll that is being paid in terms both of private property lost from eroding bluffs and public assets spent on remedial action (Quigley and Tutt, 1968; Bird and Armstrong, 1970; Gelinas and Quigley, 1973). In Ontario, around the Metropolitan Toronto area, residential, commercial and industrial properties occupy areas along the lake bluff tops where farmland, and before that Indian encampments, once lay. In the eastern suburbs of the city, Scarborough Bluffs probably represents the most intractable erosion problem along the whole Canadian coastline given the length of active shore, heavy urbanization and the close proximity to communications and utilities. The problem is further compounded inland as a result of widespread slope instability along sidewalls of the major creeks that drain to Lake Ontario and which have cut down through the same stratigraphy as exposed along the Bluffs. These, together with a distinct "scalloped" bluff crest line, add a third dimension to the problem and greatly increase the length of active slopes to be dealt with. A minimum estimate of the length of total active slope along the Scarborough Bluffs is about 33 km over a coastline length of about 16 km and with slope heights varying from 10 to 85 m. Factors such as access and ownership add further complications.

Some indication of the economic significance of the problem can be gleaned by assessing the value of land and property that would be lost given 50 years of erosion along a 1 km long section of coast. If this exercise is done, total potential losses of up to $45 million at today's prices can be identified. With the costs of remedial shoreline protection averaging about $2 million for every 1 km of shoreline the economic case for remedial work is clear.

In this report we briefly review some of the geological controls on erosion in the Scarborough area and what can be done in terms of remedial work. Many of these aspects are subject to intense local discussion among the public and engineering communities (Fig. 1) and we emphasize that no neat solutions exist. What we present here are our own observations and inferences made over the past several years in the course of ongoing surface and subsurface sedimentological studies along the Bluffs. These studies, summarized recently in a previous Geoscience Canada article (Eyles *et al.*, 1985), provide particular insight into the geological controls on erosion processes and may find applications elsewhere.

Local Setting

Scarborough Bluffs were named in 1793 by the wife of Lieutenant-Governor John Graves Simcoe for their resemblance to the imposing chalk cliffs of her native Scarborough in Yorkshire, England: "We came within sight of what is named on the

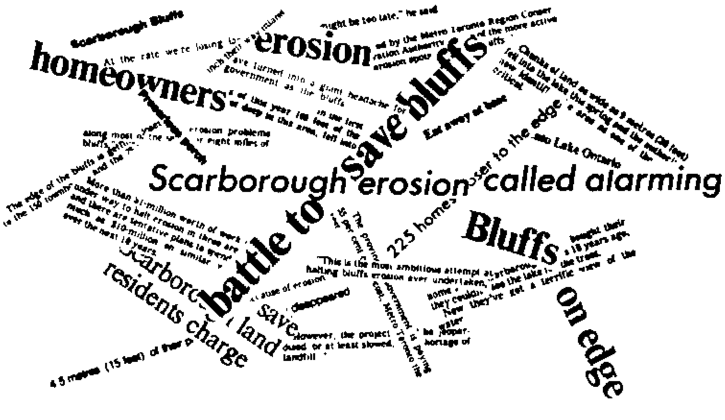


Figure 1 *Toronto media coverage as an index of community interest in erosion along Scarborough Bluffs*

map the highlands of Toronto. The shore is extremely bold and has the appearance of Chalk cliffs but I believe they are only white sand" (Innis, 1965). The Bluffs, which extend from the R.C. Harris Filtration Park in the west to East Point (Figs. 2 and 3), are considered by many to be one of the most spectacular geological sites in Eastern Canada. The highest points reach elevations of 160 m above sea level (a.s.l.) some 85 metres above the modern lake level. Much of the stratigraphy of the Bluffs has been truncated by post–glacial Lake Iroquois which cut a pronounced tableland along the cliff top at 125 to 135 m a.s.l. (about 60 m above the modern lake) at a time when the Lake Ontario Basin was still glacio-isostatically depressed (Fig. 3). Recent data indicate that the Lake Iroquois plain was abandoned at about 12,000 years before present (Fig. 2). The old lakefloor is backed inland by a now degraded and much-flattened line of bluffs fringed by fossil beach and spit systems which have been exploited for sand and gravel during explosive post–war urban development of the old lake bench (Fig. 2). This rapid growth has been maintained and is reflected in the recent construction of the Scarborough City Centre, complete with Light Rail Rapid Transit hookup to the Metro Subway system, some 4 km from the Scarborough Campus of the University of Toronto (Fig. 3). The presence of recreational areas, high density housing subdivisions, apartment complexes, condominiums and light industry in some cases right up against the eroding bluff edge is a source of great concern. This situation is the result of poor planning, starting in the 1920's, when the building of subdivisions adjacent to the large ravines that run inland from the Bluffs was initiated. In fact, it is fortunate that several plans were not carried out (Fig. 4).

A major problem is that rapid urban growth has not been accompanied by any overall regional planning for shared use of the lakeshore for residential, industrial and recreational purposes. For example, the recent construction of a large marina at Bluffers Park (with another suggested for the area adjacent to East Point; Fig. 3) is in recognition of the need to take advantage of those few areas where public access to the waterfront is still possible. As a result, major structures projecting out into the lake have been built in locations with little regard for their impact on the nearshore sediment transport system. These structures are having a major influence on the long term stability of protective beaches in areas downcurrent of the structure.

Along the Bluffs, the most critical erosion problem areas are the stretches of shoreline adjacent to South Marine Drive, Bellamy Ravine, Kingsbury Crescent and Fishleigh Drive (Fig. 3).

Rates Of Bluff Recession

Erosion along Scarborough Bluffs first became a topic for scientific discussion in the early 1850's when the westerly drift of eroded sand in the nearshore zone was recognized by Sir Sanford Fleming as the major feed for the large spit systems of Toronto Harbour (Fig. 2). A review of erosion rates and the development of slopes along Scarborough Bluffs is able to draw on many sources ranging from published topographic maps, offshore bathymetric maps, postcards, interviews with residents, geological reports and air photographs

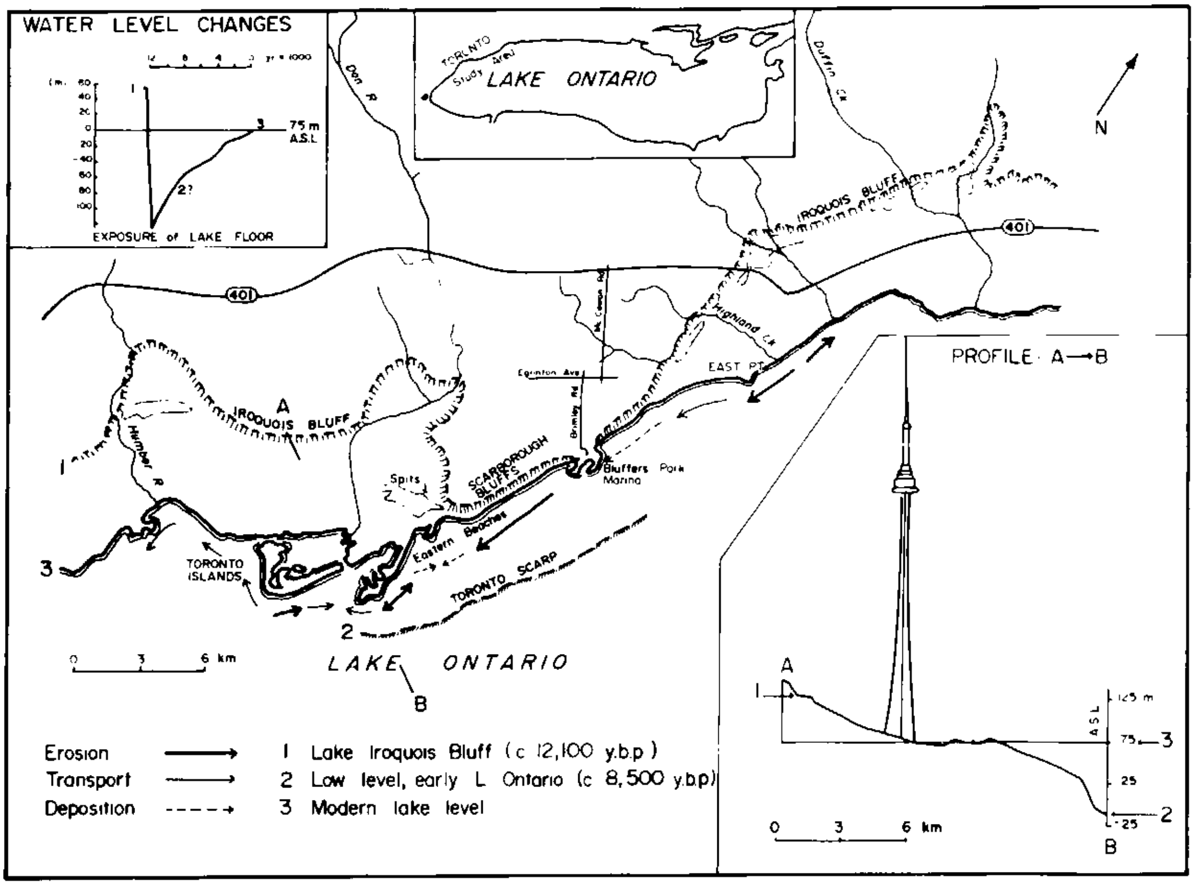
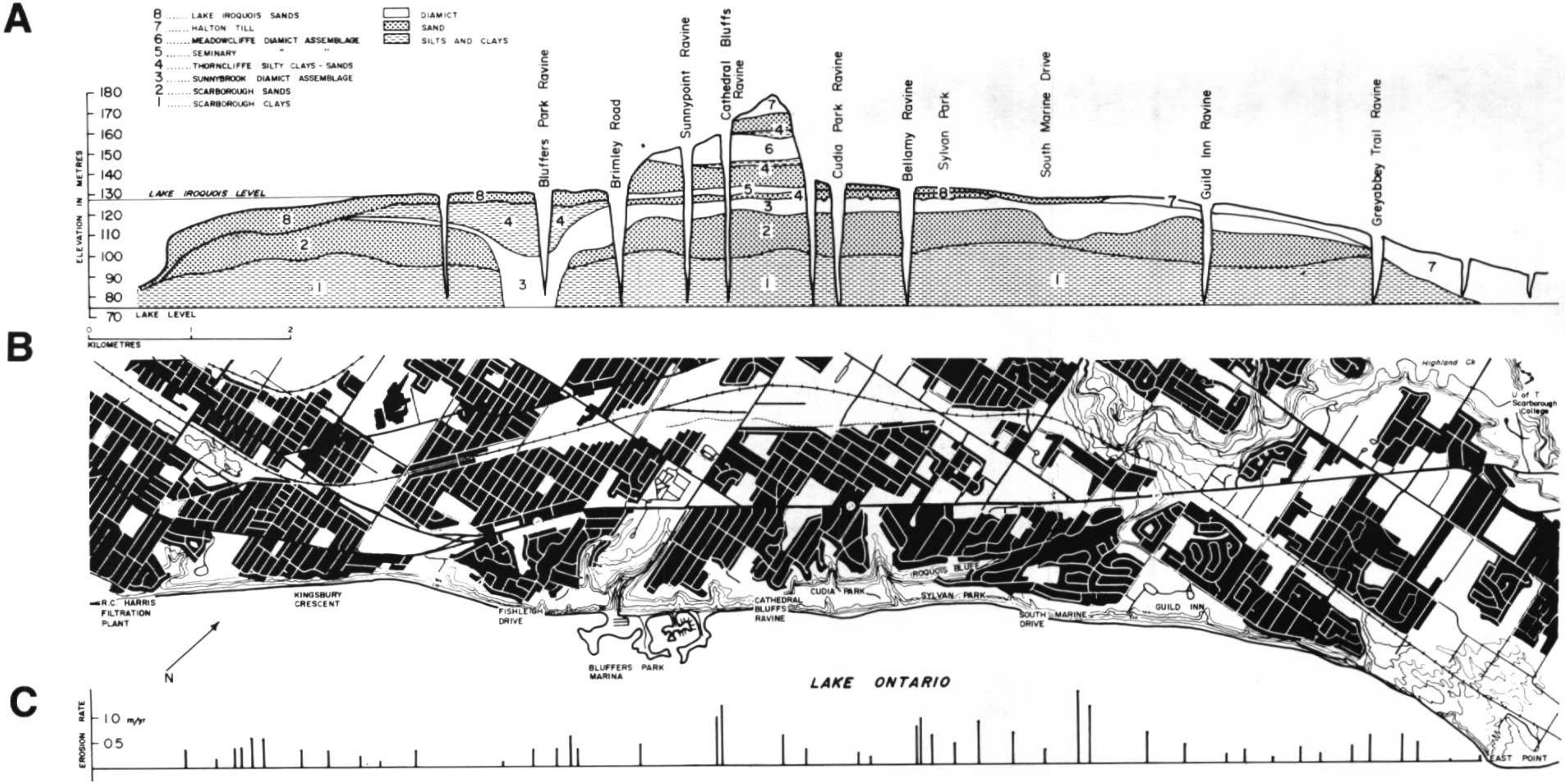


Figure 2 *Location map of the Toronto waterfront and Scarborough Bluffs; sediment eroded from the Bluffs is transported southwestward to the large spit system of the waterfront. This littoral drift system (after Greenwood and McGillivray, 1978) has been disturbed by man-made structures that project landward. Major post–glacial changes in lake level, of up to 160 m (inset after Sly and Prior, 1984), are recorded by fossil bluffs inland from the Lake Iroquois stage and a drowned scarp offshore (Fig. 10)*



D

SLOPE TYPE	planar slopes (40-50°) with shallow gullies	stepped planar slopes (50-70°) with large scallops	vertical slopes with ravines	planar stepped slopes (40-70°) with large scallops and ravines			large scale en echelon slumps	planar stepped (40-70^{b}) and vertical slopes		planar slopes (40-50°) with shallow gullies
LOCATION & DEGREE OF GROUNDWATER SEEPAGE	severe @ Scarborough sand and sand units of the top portion of Scarborough clay	severe @ Scarborough sand and sands at top of Scarborough clay moderate @ Iroquois sand	moderate @ Iroquois sand	severe @ Scarborough sand and clay moderate @ Thorncliffe sand	severe @ Scarborough sand and top of moderate @ Thorncliffe trace @ Halton Till	moderate @ Scarborough sand moderate @ Thorncliffe	moderate @ Scarborough sand & clay severe @ base of Sunnybrook diamict; fed by joints	moderate @ Scarborough sand & clay	moderate @ Scarborough sand trace @ Halton Till	moderate @ Scarborough sand trace @ Halton Till
TYPE OF EROSION	rillwash, surface sloughing, gully incision and piping	rillwash, surface sloughing, wave undercutting and piping	block failure in Sunnybrook rillwash in Iroquois and Thorncliffe sands	rillwash, mudflow, shallow sloughing and piping	rillwash, shallow sloughing, piping and wave undercutting	rillwash, mudflow shallow sloughing piping and wave undercutting	rillwash, shallow rotational failure and wave undercutting	rillwash, mudwash shallow sloughing and wave undercutting	shallow slab slumping with accumulated talus at toe rillwash and wave undercutting	rillwash, mudwash, surface sloughing and wave undercutting

Figure 3 ***A)*** *Stratigraphy;* ***B)*** *Proximity to structures and communications;* ***C)*** *Erosion rates;* ***D)*** *Slope type and activity along 14 km of Scarborough Bluffs from R.C. Harris Filtration Plant to East Point*

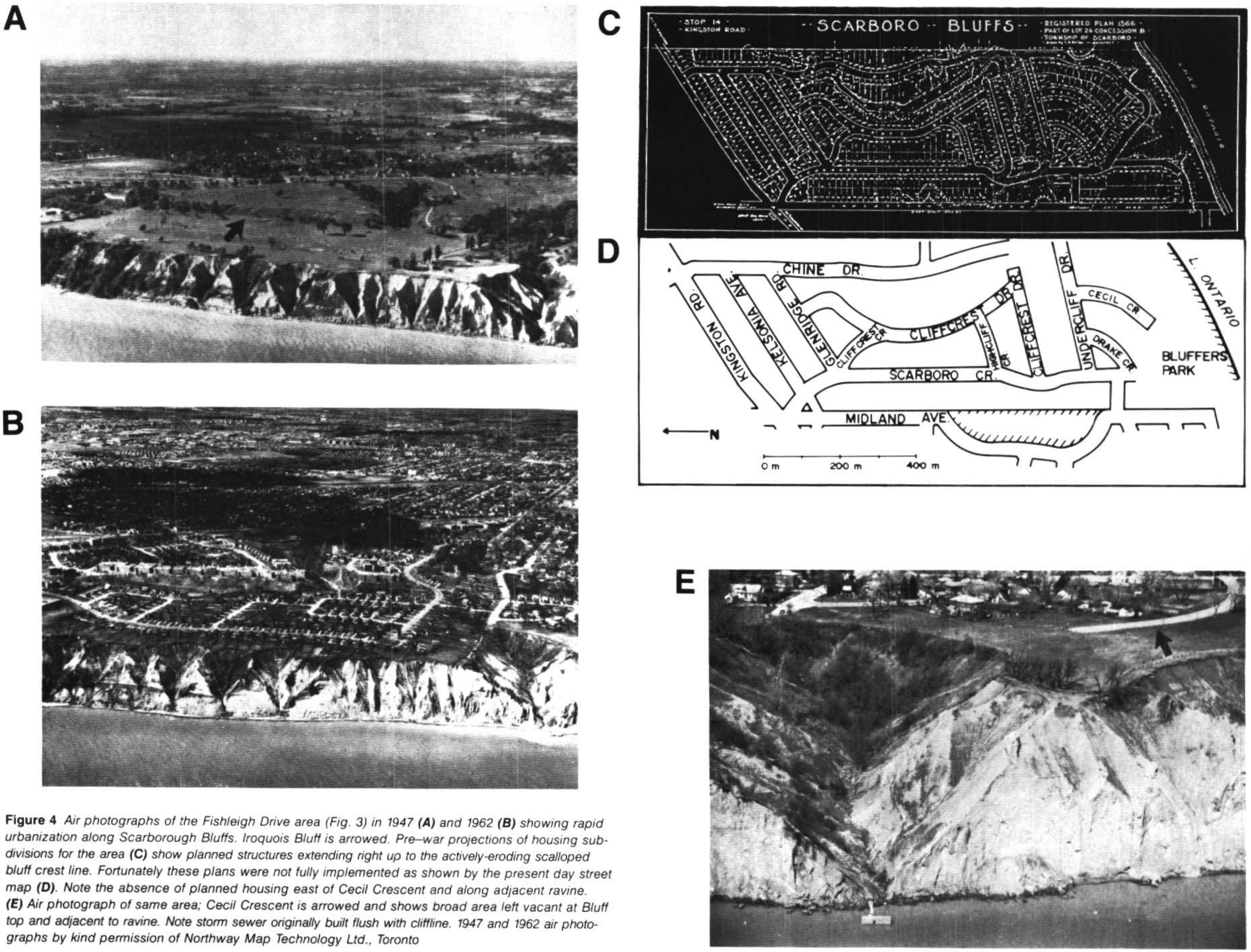


Figure 4 *Air photographs of the Fishleigh Drive area (Fig. 3) in 1947* **(A)** *and 1962* **(B)** *showing rapid urbanization along Scarborough Bluffs. Iroquois Bluff is arrowed. Pre–war projections of housing subdivisions for the area* **(C)** *show planned structures extending right up to the actively-eroding scalloped bluff crest line. Fortunately these plans were not fully implemented as shown by the present day street map* **(D)**. *Note the absence of planned housing east of Cecil Crescent and along adjacent ravine.* **(E)** *Air photograph of same area; Cecil Crescent is arrowed and shows broad area left vacant at Bluff top and adjacent to ravine. Note storm sewer originally built flush with cliffline. 1947 and 1962 air photographs by kind permission of Northway Map Technology Ltd., Toronto*

(Fig. 5). A benchmark source is the first topographic map of the area by Augustus Jones completed in 1793 during the original township survey. In 1903, Professor A.P. Coleman of the Geology Department at the University of Toronto compared the then bluff crest positions with those identified by Jones and those shown on a later 1864 map by F.F. Passmore. Coleman (1903) established an average retreat of 0.71 m yr^{-1} which compares with the averaged rates of between 0.31 and 0.76 m yr^{-1} established by more recent studies. These figures mean very little however, since they hide real annual erosion rates of between 0 and 15 m. Detailed comparisons between different studies is also complicated by problems of location and reidentification of reference points. Nonetheless, these figures allow rough computations to be made of the total volumes of eroded sediment being added to the nearshore lake sediment system each year. For example, an annual average loss of 0.5 m yr^{-1} represents some 400,000 m^3 of sediment. These figures are comparable to data available for other eroding coastlines of unconsolidated Quaternary glacial sediments in the Great Lakes Basin (Gelinas and Quigley, 1973; Haras and Tsui, 1976; Quigley *et al.*, 1977). What makes the loss at Scarborough so critical, however, is that erosion is occurring in a heavily urbanized area. As early as 1912, in an unpublished report to R.C. Harris, then Commissioner of Works at City Hall, Coleman argued that a wide verge be left empty inland of the cliff crest. He argued that no structures should be allowed within this "*cordon sanitaire*" which was recommended to be sufficiently broad to allow for at least 200 years of erosion. The plans for cliff top subdivisions conceived in the 1920's (Fig. 4) suggests that the real value of this advice was not realized.

There is the suggestion, as yet unsubstantiated, that the rapid urbanization of the bluff top tablelands which Coleman sought to prohibit has in fact accelerated erosion rates. A.P. Coleman, in 1933, argued that deforestation of the Bluff tops has been instrumental in the creation of large ravines since the Passmore survey of 1864. Bryan and Price (1980), in a review of erosion rates since 1922, showed that the rates of crestal retreat between 1952 and 1976 were markedly higher than those for the preceding 30 years. One way in which development has lead to greater erosion in certain localities has been by the urbanization of the catchment areas of large ravines that cut down through the stratigraphy of the Bluffs. Bellamy Ravine is an outstanding example of a ravine that has been substantially enlarged by uncontrolled storm run-off from paved areas (Fig. 6). Even today this run-off is vented directly into the ravine with only minimal attention paid to the accelerated downcutting that occurs at periods of "flashy" summer thunderstorm run-off. The emptying of swimming pools from nearby homes over the bluff edge has also been observed and there is also the suggestion that these and subsurface utilities such as water mains, sewers and septic tank systems are leaking. These processes must also be seen in the context of man-made disturbance of the nearshore littoral drift of sediment by the construction of groynes by local landowners and at Bluffers Park by a large marina (Figs. 2 and 3). Areas upcurrent are experiencing rapid beach aggradation while downcurrent areas are starved of sediment and beaches are being stripped such that waves now impinge directly at the bluff face.

The littoral drift system established along the coastline between the Toronto waterfront in the west and Highland Creek in the east involves a general southwesterly movement of sediment (Fig. 2). In this way sediment eroded from the Bluffs each year (about 400,000 m^3) is sorted (mud fractions escape out into the deeper lake basin; about 375,000 m^3) and sand (about 25,000 m^3) is moved downcurrent to the large spit systems at Toronto (Fricbergs, 1970; Lewis and Sly, 1971); very little sand-size material bypasses the spits. This drift system forms in response to wave energy impacting on the shoreline and involves a predominantly longshore movement of sediment. The system is complex, responding in different ways under various wave conditions, and is difficult to model (Greenwood and McGillivray, 1978, 1980). For example, the most damaging waves moving into the shoreline of the Bluffs move in from the east (the direction of longest fetch; 200 km) and when combined with the high lake levels generated by snow melt can accomplish substantial toe erosion.

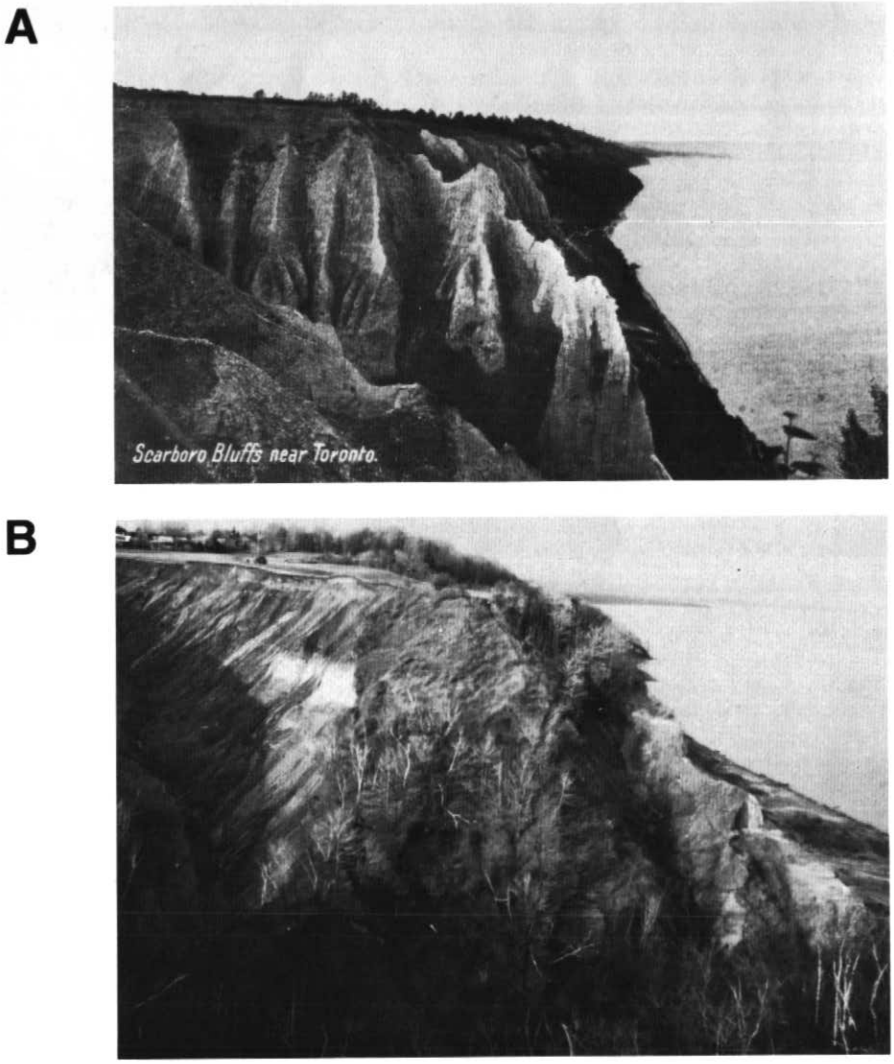


Figure 5 ***A)*** *Popular postcard of the early 1920's, depicting the view east from Sunnybrook over Cathedral Bluffs with their intensely dissected slopes and arêtes resembling cathedral buttresses. The present day view* ***(B)*** *shows largely planar slopes; it is evident from other evidence that gully and arêtes experience cyclic development over time from planar slopes to well-developed gully systems*

These waves are not moderated by an ice cover which rarely develops on Lake Ontario. However, such damaging wave conditions occur infrequently. In contrast, the long-term littoral drift system is maintained by waves from the southwest. This is the prevailing onshore wind which, because of the limited cross-lake fetch (30 km), generates low-amplitude (<2 m), high-frequency waves (Greenwood and McGillivray, 1978). Modelling of the natural drift system, developed under average wave conditions, identifies stretches of coastline subject to either net erosion, transport or deposition of sediment (Fig. 2). This system of erosion and downcurrent deposition is very sensitive to man-made changes. Unnatural disturbance was first noticed in the first decade of the present century when local lakeward projecting structures were built to safeguard water intake and discharge pipes (e.g. Fig. 7). Construction of the R.C. Harris Filtration Plant in the first decade of the twentieth century greatly restricted the westward movement of sand into the Eastern Beaches necessitating artificial beach feeding and seawall construction (Greenwood and McGillivray, 1978, 1980; Figs. 2, 3 and 8). Piecemeal construction of groynes, often by the simple method of sinking barges, has resulted in many more local examples of downcurrent stripping of protective beaches and rapid upcurrent accumulation.

Away from local areas where higher post–urbanization erosion rates can be clearly demonstrated, it is apparent, however, that on a longer time-scale, average rates of bluff recession determined since 1793 have been maintained for at least 8,500 years. Evidence for this is to be found offshore where mapping of the bottom topography adjacent to the Bluffs has revealed a low-relief sloping littoral shelf, the outer margin of which is defined by the 30 m water depth contour. At this depth a distinct scarp face up to 30 m high (the Toronto Scarp; Fig. 2) can be identified dropping steeply to deeper water. The scarp parallels the modern lakeshore cliffline and degraded Iroquois Bluff inland and has clearly formed by erosion along a lakeshore at a time when the lake level was some 60 m below the modern level. The age of this early Lake Ontario shoreline can be approximated using recent data on post–glacial water level changes in the western section of the Lake Ontario Basin presented by Sly and Prior (1984); an age of around 8,500 years before present is indicated (Fig. 2). Since that time lake levels have risen in response to differential isostatic recovery and uplift of the lake outlet along the St. Lawrence River leaving a drowned, relict scarp offshore. The low relief of the littoral shelf above the Toronto Scarp reflects progressive erosion back

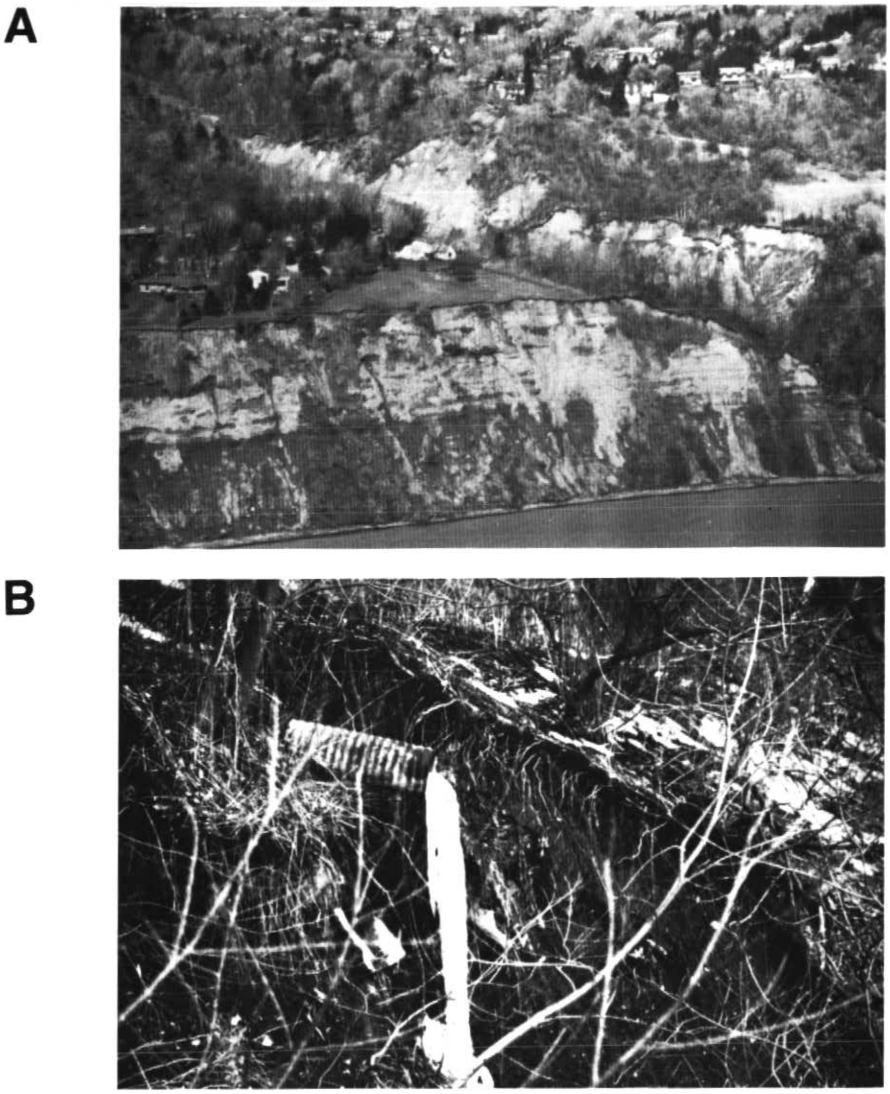


Figure 6 *A) Bellamy Ravine, one of the most impressive of the ravines along Scarborough Bluffs. Its headward development and rapid downcutting have been aided by rapid urbanization of its catchment (Fig. 4) and uncontrolled storm runoff* ***(B)***

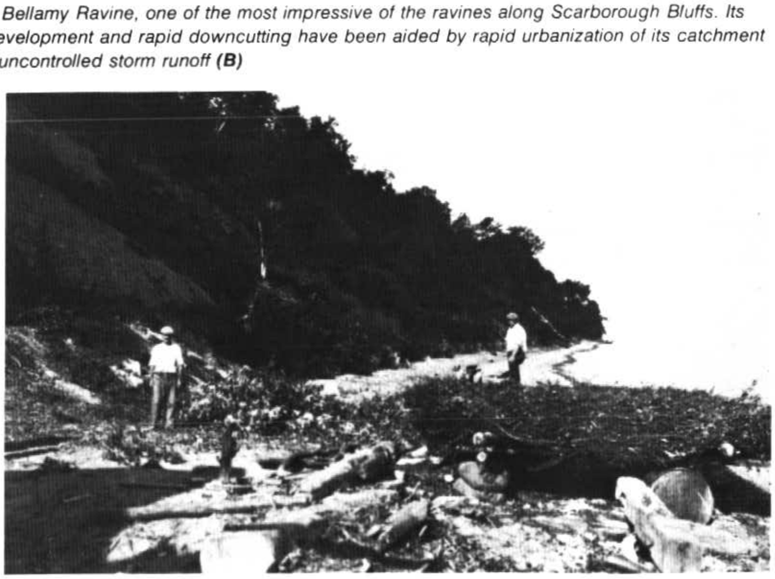


Figure 7 *Early attempts at remedial work: "Mississippi mats" constructed by laying brushwood, mostly willow, on a wooden frame, being placed around the intake for the Scarborough Waterworks (Fig. 3) in the mid 1930's (from the collection of A.P. Coleman)*

to the present bluff line and the width of this scoured, wave-cut platform can be used, in a crude sense only, to identify the average rate of bluff recession over a time span of 8,500 years. The maximum width of the shelf is about 5 km suggesting an averaged annual rate of recession of about 0.58 m yr^{-1}. This is in the mid-range of the erosion values that have been measured since 1793 (0.31-0.76 m yr^{-1}) suggesting that the estimated age of the Toronto Scarp is approximately correct. It is stressed that little is known of this important lake floor geomorphic feature and it may well be that the origin of the scarp reflects a longer and more complex history (Lewis and Sly, 1971).

Figure 8 *View looking west of the Eastern Beaches (Fig. 2) toward the downtown core showing groynes and resulting entrapment of littoral sediment transported by the long shore drift system*

Geology and Slopes

The key to understanding the patterns of erosion and their expression as different slope types along the Bluffs, is to be found by considering the sedimentology of the stratigraphic units preserved in the Bluffs (Fig. 3). The exposed stratigraphy is essentially a cross-section through a succession of lake basin sediments deposited over the last 100,000 years at times of high lake levels. The most extensive unit is a thick upward-coarsening deltaic package that at lake level is composed of laminated prodelta silts and clays (Scarborough Clays) which show an increasing number of sand interbeds up-section, recording the progradation of a major sand body (Scarborough Sands). This delta body was deposited over an area approaching 200 km^2 both along and at the mouth of a large bedrock channel connecting Georgian Bay to Lake Ontario, via Lake Simcoe (the Laurentian Channel, part of the relict "pre–glacial" drainage system of the Great Lakes (Eyles *et al.*, 1985)). The regional slope of the delta surface can be reconstructed in the subsurface, and falls from about 180 m near Barrie to 120 m a.s.l. at the Bluffs. Large channels, up to 1 km wide and up to 60 m deep, can be identified on the delta surface exposed along the Bluffs. The origin of these channels is unclear; they may record either lowered lake levels, the original distributary channel system on the delta surface, or increasing fluvial discharges resulting from either redirection of drainage or the entry of ice sheet margins into the area. The latter may be important because the relief on the delta top is infilled by a succession of glaciolacustrine deposits consisting of alternating diamict units (pebbly glaciolacustrine muds) and sands and silts. The origin and age of these sequences has been the subject of a number of recent papers and discussions summarized by Eyles and Eyles (1984) and Eyles *et al.*, (1985).

A

Figure 9 ***A)*** *Icicles marking horizons of "pipes" formed by subsurface water seepage along juxtaposed sand and mud lithologies at the contact of the deltaic Scarborough Sands and Scarborough Clays (Fig. 3)*

The stratigraphy of the Bluffs records sedimentation in a series of high-level lake

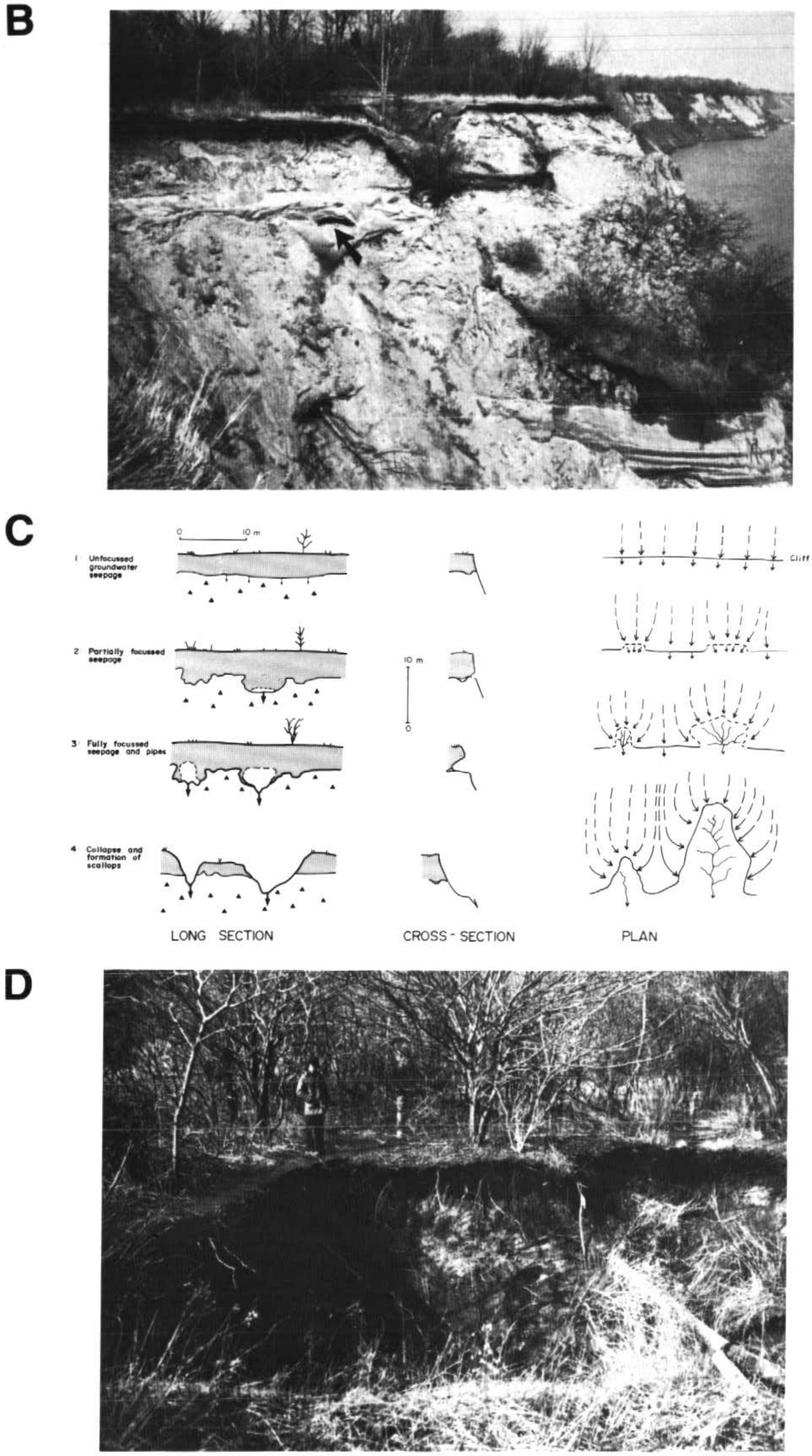


Figure 9 ***B)*** *Large cave-like pipe (arrowed) associated with "sag basins" of sand formed by soft-sediment deformation on the upper surface of diamict units;* ***C)*** *2 to 4: the formation of large erosional scallops, by spring sapping, in response to groundwater focussing within "sag basins" on top of impermeable Sunnybrook diamict in the area of Sylvan Park (Fig. 3). Unfocussed seepage occurs where no sag basins are present (1);* ***D)*** *Head of scallop showing collapsed area over subsurface pipe*

bodies ponded to at least 90 m above modern lake level. Ice damming of the St. Lawrence or isostatic subsidence in response to regional ice sheet loading may be the cause of this high level ponding. Sedimentological, paleoecological and paleomagnetic studies suggest that the diamicts were formed as glaciolacustrine muds with floating ice rafting in coarser grain sizes. Three diamict units (Sunnybrook, Seminary, Meadowcliffe; Fig. 3) are separated by intervals of deltaic facies that coarsen upward from laminated silty clays to sands. The significance of this alternation between deltaic sediments and fine-grained diamict facies is that beds of contrasting permeability are superimposed within the stratigraphy of the Bluffs resulting in confined groundwater aquifers; it is the release of this groundwater on the bluff face which is the principal control on slope stability. Figure 3 shows the stratigraphic location of seepage zones along the Bluffs. The principal zones of seepage occur along the contact of the Scarborough Sands and Clays, within the Clays, and on the tops of the diamicts illustrating the development of "perched" watertables (Figs. 3D and 9A). The upper surface of the diamict units are commonly irregular showing large basins of the overlying deltaic sands loaded down into the diamict (Fig. 9B). These are "sag basins" reflecting the rapid lacustrine deposition of sand over a low-strength muddy substrate and the soft-sediment loading of sand. These basins act locally to focus perched subsurface groundwaters moving lakeward to the bluff face where emerging water creates large cave-like "pipes" (Fig. 9C). These enlarge rapidly at times of spring snow melt and lead to the downslope failure of the overlying sediment column (e.g. Pierson, 1983). Load casts on the surface of the Sunnybrook diamict (Fig. 3) and the associated processes of spring sapping identified in Figure 9 are a major influence on the location and subsequent headward erosion of the large erosional bowls or "scallops" along the Bluffs. This is particularly the case in the area west and east of Sylvan Park where the Sunnybrook diamict outcrops toward the top of the cliffline (Fig. 3).

Slope Types

A very simple classification of slopes along the Bluffs recognizes two major slope types: steep *planar* slopes that show either a flat or "stepped" profile together with a largely straight cliff-crest line, and "*scalloped*" slopes with a deeply indented cliff-crest line defined by large erosional bowls (Fig. 3). In addition, along one section of the Bluffs, at South Marine Drive, moderately steep slopes are undergoing failure by shallow rotational slumping (Fig. 3). Although planar and scalloped forms are the predominant slope types along the Bluffs, the highest erosion rates are associated with slopes undergoing rotational failure.

Planar slopes are undergoing parallel retreat in response either to groundwater seepage and piping (Fig. 9), with associated sloughing of surface sediment, or by minor, shallow, slab-like slides along the stress relief joints parallel to the cliff face (Fig. 10). Both these processes are most active in the spring. Debris accumulates at the slope foot as debris flows, which subsequently stabilize as a thick talus slope, and is removed during the following summer and fall by wave activity. Data indicate that during the winter, groundwater is prevented from escaping and high porewater pressures build up behind the frozen face to be released very rapidly as the slope thaws (Fig. 11). The role of freeze-thaw activity in acting to elevate porewater pressures in slopes and promote "spring sapping" is well-known in seasonally-cold climates. On the steeper slopes in areas of lithological homogeneity, slab-like masses of sediment are released from stress relief joints and accumulate as a steep talus slope at the cliff foot. The best example of this activity is seen to the west of Bluffers Park where the stratigraphically lowermost diamict unit and associated fine-grained facies fill in one of the large channels on the delta "basement". Here the entire cliff, up to 50 m high, overhangs the cliff foot in a series of spectacular arêtes (Fig. 10A). The progressive degradation of a large "needle"-like arête can be shown very clearly by a sequence of photographs taken by the late A.P. Coleman in the years between 1900 and 1936 (Fig. 10B). Individual arêtes are defined by deeply-cut gullies and resemble large cathedral buttresses (hence the name Cathedral Bluffs; Fig. 3). Erosion appears to have been accelerated along this stretch of the coast as a result of the beach starvation and stripping caused by the Bluffers Park Marina, though the magnitude of wave impact stresses at this site has yet to be determined.

Scalloped slopes, unlike the planar slopes described above, are not stable forms and appear to undergo a distinct sequential evolution. Immature scallops narrow downward and discharge via chutes well above lake level. The predominant process occurring within the scallop is spring mud flow activity and subsequent summer fluvial dissection by rills. Scallops enlarge by headward retreat and downcutting and are separated by large arêtes fronted by steep planar slopes described above (Fig. 12). The role of "sag basins" on the upper surface of the Sunnybrook diamict in focussing groundwater seepage and accelerating scallop growth rates has already been discussed above (Fig. 9). The scallops are self-maintaining by virture of the steep hydraulic gradient set up around the head of the scallop and the strongly focussed groundwater seepage that occurs. Adjacent arêtes are well-drained and stand at a very high angle leading to a further concentration of erosional activity along the scallop axis. With continued downcutting the groundwater table is intersected (most commonly in the delta sands) and perennial groundwater seepage and stream drainage becomes established. At this stage scallops undergo accelerated downcutting and headward growth to become ravines which are particularly susceptible to uncontrolled urbanization of their catchment areas (e.g. Bellamy Ravine, Fig. 6). The sideslopes of the ravines are often of the planar type and exhibit deeply-cut rills separated by large buttresses and spires similar to those seen at Bluffers Park (e.g. Cathedral Bluffs Ravine, Fig. 3). Slope failures, in the form of large tabular sediment masses released from stress-release joints, are accompanied by seismic tremors that can be felt in adjacent residential properties. A program to measure the frequency of slope activity by reference to recording seismographs is currently under development.

Slopes undergoing rotational failure are restricted geographically to a single sector of the Bluffs, in the area of Livingston Road and South Marine Drive, where specific geological and groundwater conditions apply (Fig. 3). However, despite the limited extent of this slope type, such slopes are associated with the highest erosion rates along the entire coastline. In this area the moderately steep cliffline is degrading in the form of shallow rotational failures that undergo remoulding and softening downslope to form debris flows that project out into the lake until removed by wave erosion. Episodes of recent slumping can be correlated very well with periods of intense snow melt that occur either during or at the end of the winter. It is no coincidence that it is in this area that another major paleochannel, cut into the top of the Scarborough Sands delta, is exposed in cross-section. This channel has cut down through the upper sandy part of the delta into the underlying prodelta muds (Scarborough Clays). The base of the channel is floored by

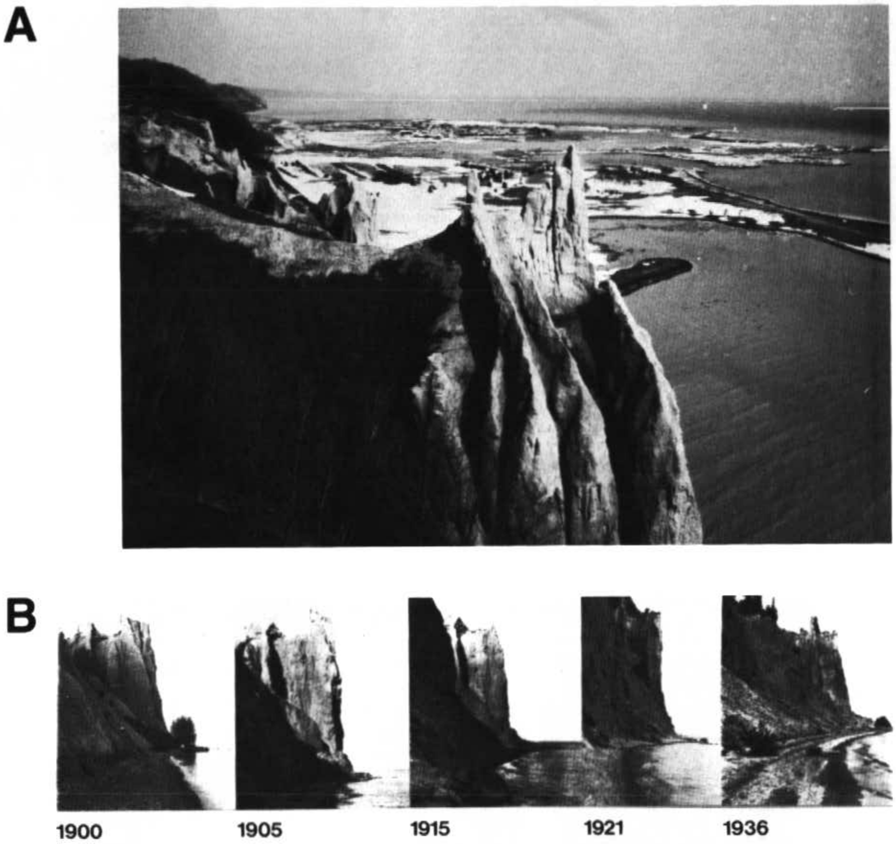


Figure 10 ***A)*** *Vertical planar slopes up to 50 m high, in the form of "needle" arêtes separated by erosional scallops. Slopes are cut in diamict and associated silty clays (in the area of Bluffers Park Marina) (Fig. 3);* ***B)*** *Progressive degradation of a "needle" arête between 1900 and 1936 (from the collection of A.P. Coleman)*

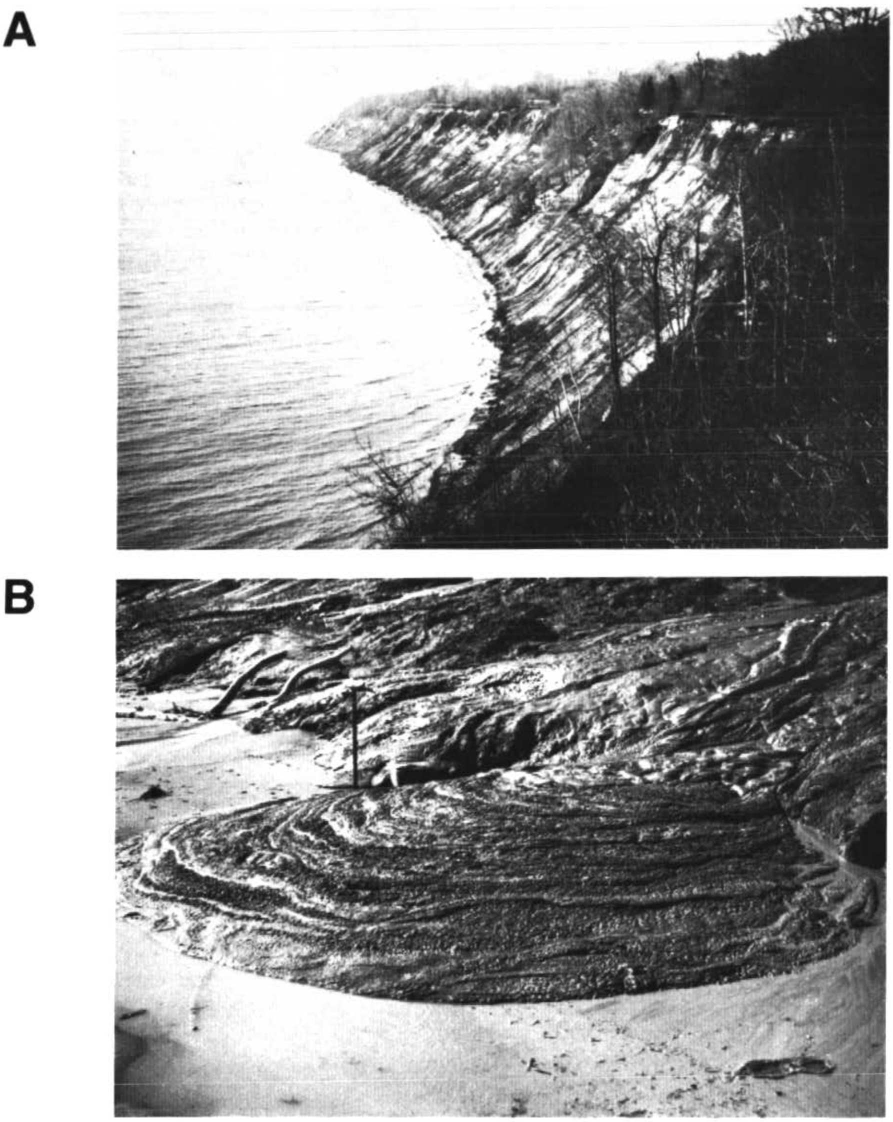


Figure 11 ***A)*** *Planar slopes at time of maximum spring snow melt; mudflows are moving downslope and have covered the beach area* ***(B)****. Thaw of frozen bluff sediments allows high porewater pressures, built up behind the frozen face, to be dissipated thereby releasing water and generating mudflow activity. Note oblique wave approach to the coast which is responsible for littoral drift system (Fig. 2)*

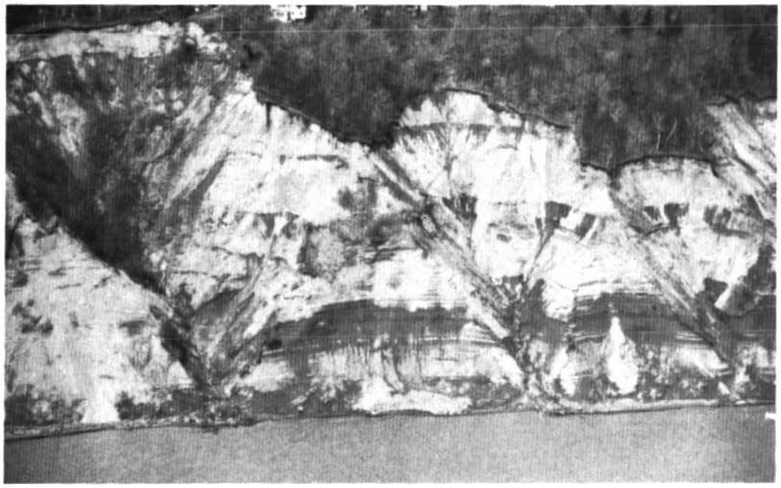


Figure 12 *Large erosional scallops in various stages of development (see Fig. 9C). Note proximity of structure at top left centre*

coarse lag gravels and reworked diamicts and has been plugged by impervious diamict. It is this plug which may be acting as a constriction to the free release of groundwaters moving lakeward along the axis of the channel. Piezometers installed in a borehole a few metres inland have recently identified high piezometric pressures in the deltaic sands adjacent to the channel. There is also very strong evidence that the channel axis is being recharged during periods of snow melt by meltwaters penetrating along deep joint systems in the diamict unit (Sunnybrook, Fig. 3A) that caps the channel (Fig. 13). Well-developed vertical joint systems are characteristic of the diamict units outcropping along the Bluffs and these structural discontinuities greatly increase bulk permeability to values an order of magnitude greater than unfractured diamict. Their distribution and orientation has not been systematically studied along the Scarborough shoreline, but, at a few locations where measurements have been made, the dominant joint sets appear to have an orientation that parallels the trend of paleovalleys cut into the underlying shale bedrock (Eyles *et al.*, 1985; Fig. 13). The coincidence of joint sets in surficial sediments and structures in underlying bedrock is commonly reported (e.g. Grisak *et al.*, 1976) and can be explained either by differential compaction or crustal flexuring during glacioisostatic rebound.

To a large extent the slope instability along the South Marine Drive area is self-maintaining because the fine-grained slump debris that mantles the lower slope forms an effective cap to the free release of groundwater. This largely impermeable debris cover is known to result in over-pressuring behind the slope face such that the larger failures are commonly accompanied by the release of large volumes of groundwater that had been dammed-up within the slope. Whereas the groundwater conditions described above are limited along the Bluffs to the area of South Marine Drive, similar processes occur inland at several localities along the sidewalls of river valleys. These exposures reveal the same system of paleochannels on the upper surface of the Scarborough Sands, and are sites of enhanced spring sapping as a result of the disturbed groundwater conditions generated by these channels. In this way, an understanding of the subsurface geometry of the stratigraphic units in the Scarborough area together with an assessment of the paleogeographic evolution is helping to rationalize the occurrence and distribution of valley side slopes that are particularly susceptible to spring sapping.

There are interesting comparisons to be drawn between the form of many creeks adjacent to Scarborough Bluffs and the river valleys of other regions that are being

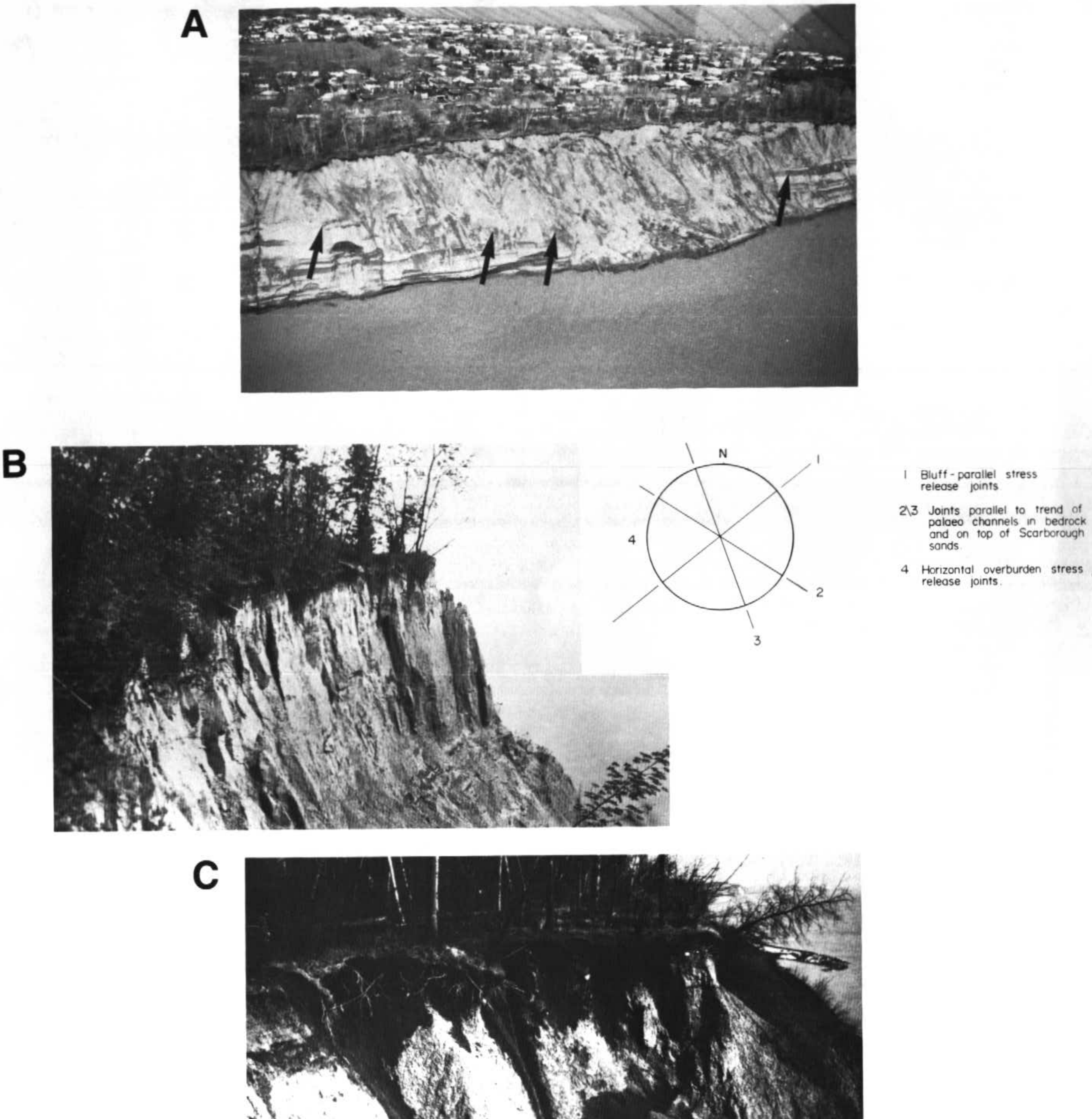


Figure 13 ***A)*** *Air photograph of multiple shallow rotational failures involving diamict in the area of South Marine Drive. Sunnybrook diamict fills a paleochannel (arrowed) cut into the underlying Scarborough Sands (Fig. 3);* ***B)*** *Joint sets affecting Sunnybrook diamict and penetrating into underlying Scarborough Sands. Numbers refer to relative order of importance of joint sets in South Marine Drive area;* ***C)*** *Surface derived snow meltwater emerging under pressure (arrowed) from joints exposed along open bluff face (March 1985). Joint fed recharge to sands at the base of the paleochannel (Fig. 3) results in high porewater pressures particularly where free release of water is prevented by a mantle of slump debris. Periods of rotational slumping are observed to be associated with release of water from slope*

cut down through alternations of pervious and impervious rock types. Laity and Malin (1985) have recently drawn attention to the important geomorphic role of spring sapping in the Colorado Plateau area where deeply entrenched valley systems widen abruptly in the form of subsidiary "amphitheatre-headed" valleys. These are attributed to continued spring sapping along side slopes of the main valleys along pervious sandstones (see also Higgins, 1984). Comparable examples of abrupt increases in valley width are found along the creeks draining to Lake Ontario and are associated with continuing mass movement processes. The source of the groundwater has been discussed by both Coleman (1933) and Haefeli (1972) who argued for a regional groundwater system contained within the infill of the bedrock Laurentian Channel, with regional flow southward from Georgian Bay toward Scarborough Bluffs and Lake Ontario.

Remedial Work

The Metropolitan Toronto and Region Conservation Authority was formed in 1957 largely as a result of fatal flooding caused by Hurricane Hazel in 1954. The Authority is ultimately responsible under its waterfront development program, for acquiring a publicly owned landbase which will provide new access points to the lakeshore and for implementing erosion control measures along the Scarborough shoreline. The Authority anticipates, according to recent estimates, a total budget allocation of about $10 million over the next 10 years for erosion control projects. Several geotechnical studies have been commissioned to date, and there appears to be general agreement that the most desirable programme overall would be prevention of toe erosion, regrading and drainage of the bluff slope (Fig. 14). In certain areas, slope-foot berms can be built to prevent toe erosion and the crest could be allowed to retreat naturally at low cost resulting in a generally lower and more stable slope form. Slope stability can be aided by benching the slope. In this case, remedial work does not mean maintaining the present cliff-crest line since flattening of the slope will move the cliff-crest inland (Fig. 14A). This approach clearly is applicable only to those zones where structures, communications and utilities are at some distance from the cliff-crest. In other locations, the close proximity of structures prohibits slope flattening and the necessary cliff-crest recession that is involved, and large volumes of fill are required to achieve a flatter slope (Fig. 14B). In these areas, as along Kingsbury Crescent and to the west of Guild Inn where two apartment complexes and a condominium are within several hundred metres of the crest, prevention of toe erosion and backfilling is currently being pursued (Fig. 15). In extreme cases, individual house structures can be lifted from their foundations and moved inland.

It is widely recognized that remedial work along the bluffs must not interfere with the release of groundwaters from bluff slopes because prevention of free drainage rapidly leads to increases in porewater pressures and increased slope activity. For this reason, in those zones where householders have dumped fill from the cliff-crest, this practice has largely promoted instability rather than led to its reduction. Studies along the Bluffs have indicated the formation of high piezometric pressures where the discharge of groundwater is prevented by talus cover.

Escaping waters from groundwater seepage zones need to be intercepted by suitable drainage systems and marshalled away from the bluff face in order to prevent dissection and debris flow activity. In the few areas that this has been done by private landowners there have been significant reductions in erosion rates. Drainage work must be done in conjunction with reduction in the slope angle, benching and, where necessary, the construction of toe protection from direct wave attack. Construction of groynes results in local beach build-up and toe protection but this is at the expense of adjacent properties downcurrent whose beaches become starved and ultimately disappear. Figure 7 shows early attempts at carrying out toe protection using "Mississippi mats" composed of brushwood on timber frames. Modern slope-foot berms "armoured" to withstand winter storms are shown in Figures 14 and 15.

The problem of groundwater control on the stability of long and steep slopes is widely encountered in the mining industry where the impact of groundwaters on the stability of long steep slopes can be a significant operating factor in large open-cast mines. The many techniques that have been used to control groundwater-generated instability in pit side-slopes (e.g. Fig. 14) could be applied directly to the Bluffs and a good argument can be made for a series of large-scale field trials in order to assess the effectiveness of techniques such as pumped-well curtains during critical periods of spring snow melt. This work requires detailed three-dimensional reconstruction of the geometry of individual stratigraphic horizons paying particular attention to the

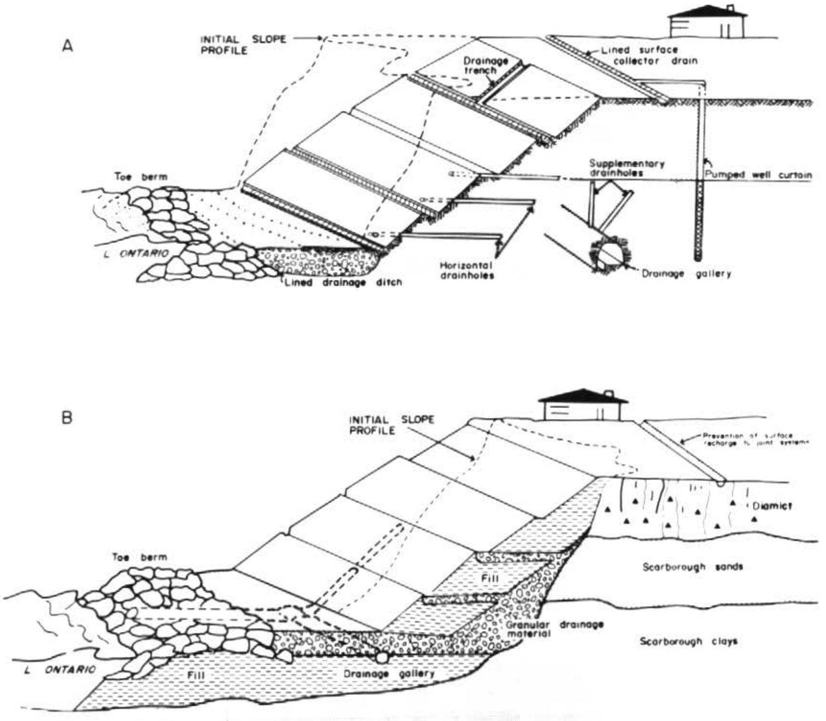


Figure 14 *Contrasting slope control and drainage systems.* ***A)*** *Situation where siting of pre–existing structures permits natural or artificial lowering of the bluff slope angle;* ***B)*** *Situation where pre–existing structures are in close proximity to bluff edge and the slope profile has to be lowered by addition of fill. Note toe berms in both cases to prevent the erosion and to buttress lower slope area.*
After various sources, principally CANMET (1977)

distribution of permeability barriers, their shape, preferred orientation, dip, tendency to bifurcate, etc. within the thicker pervious units. This data is required in order to identify the most effective location of pumped wells. Much of this data has already been collected in the course of comparative studies between the Bluffs and similar Pre–Quaternary glacial sequences containing significant hydrocarbon reserves in attempts to better understand trapping mechanisms and reservoir characteristics for enhanced recovery schemes. Thus, in this instance, the reservoir geologist and the slope engineer are asking essentially the same questions with regard to the movement of fluids through the sediment sequences.

Clearly, more data are needed as to the origin and age of the groundwaters that are controlling slope activity along the shoreline of the Bluffs . The nature of the regional groundwater system discharging southward along the Scarborough Sands has been discussed by Coleman (1933) and Haefeli (1972; see above). The importance of local recharge, through jointed diamict units, has also been identified in this study along the cliff-crest line (Fig. 13). In addition, Bird and Armstrong (1970) suggested that the regional groundwater flow to the Bluffs was augmented by recharge from nearby creeks such as Highland Creek. This river flows parallel to the lakeshore for several kilometres (Figs. 2 and 3) and is floored along much of its length by Scarborough Sands. Recharge from the creek bed was argued to be a major source of groundwater moving southward to the eroding Bluffs, though this argument remains to be rigorously assessed in the light of geochemical studies aimed at pinpointing the origin of groundwaters.

A major source of concern stems from trying to predict the long-term behaviour of the slopes of the Bluffs once remedial work has been carried out. At the present time, major, deep-seated slope failures involving large volumes of sediment are not found along the Bluffs. This situation has been maintained since at least 1793 (see above) under conditions of high rates of Bluff erosion and continued trimming back of the Bluffs. Remedial work would radically change this situation to one where major slopes were stabilized in one position. Given well-documented, long-term and progressive reductions in the shear strength of over-consolidated clays in response to weathering, stress relief and increasing moisture content (Skempton, 1964), there is the possibility that large, deep-seated failures might occur after a long lag time and with catastrophic results. This concern applies in particular to the Scarborough Clays which outcrop at lake level along much of the shoreline of the Bluffs (Fig. 3). Quigley *et al*. (1971) have shown, for example, that laboratory testing of the shear strength of the Scarborough Clays may considerably overestimate long-term values of shear strength that develop in natural slopes. This appears to be the result of the progressive alteration of swelling clays (a form of montmorillonite derived from vermiculite) present in these prodelta sediments.

Another problem in predicting slope behaviour centres on the effects of long-term changes in lake level. The level of Lake Ontario (mean = 74.0 m a.s.l.) is rising at a steady rate of 0.3 m per century as a result of faster isostatic uplift of the lake outlet along the St. Lawrence River (Clark and Persoage, 1970). Superimposed on this rising trend are long-term (decadal) fluctuations of up to 2 m generated by precipitation trends, and short-term seasonal fluctuations of about 1.3 m generated by snow melt. A general relationship between high lake levels since 1950 and the frequency of slope activity along the Bluffs is evident from study of air photographs since 1947. This relationship is well-documented throughout the Great Lakes Basins (Haras and Tsui, 1976). The mid-to-late 1950's and around 1970 and 1980 were times of high lake level and enhanced slope activity. However, whereas high lake levels result in more effective removal of slope foot talus and may thus promote slope instability, the primary cause of such slope instability must be increased precipitation to which the lake level is also responding.

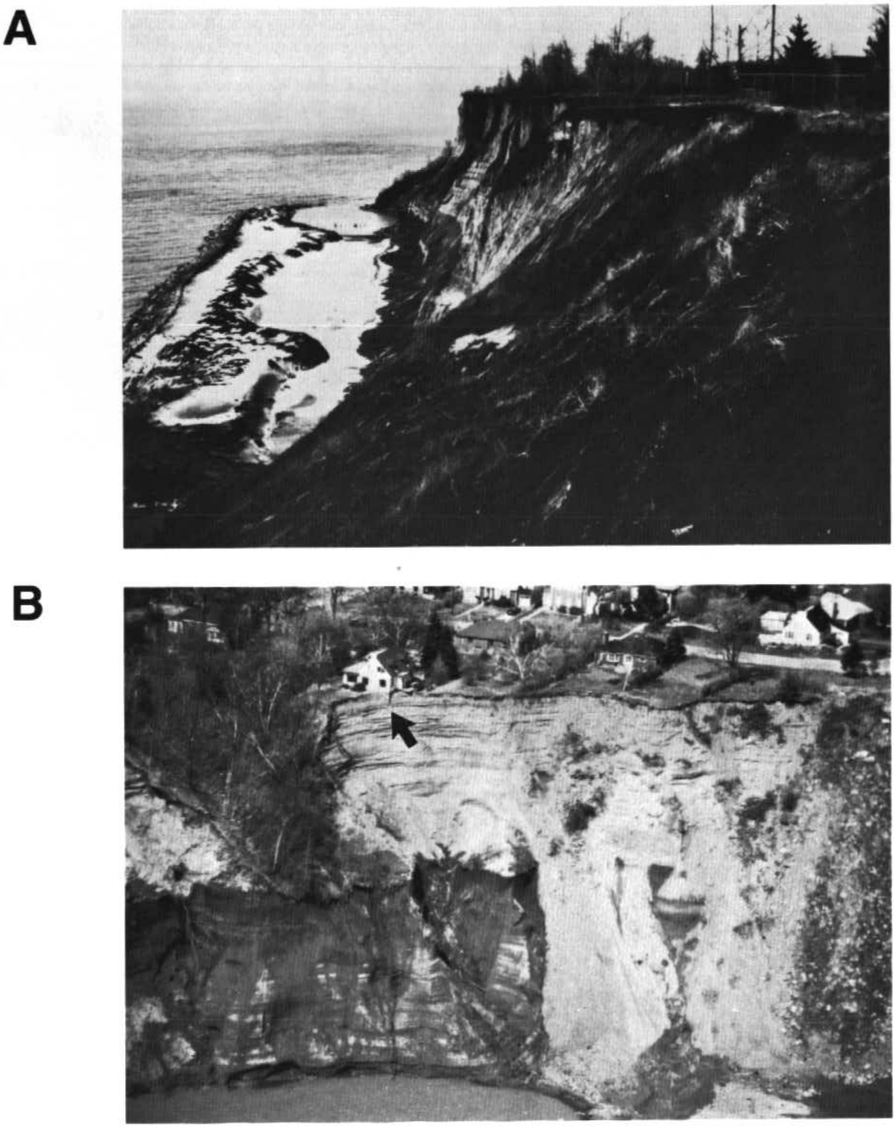


Figure 15 ***A)*** *Example of toe berm being built along an actively eroding bluff foot in the area of 75 townhouses at Livingston Road (Fig. 2). The use and construction of "armoured" beach berms in the Toronto area is discussed by Denney and Fricbergs (1979);* ***B)*** *Bluff slope angle being lowered by addition of fill (Fig. 14B) in the area of Kingsbury Crescent. The house close to the edge (arrowed) has since been jacked up and moved inland*

In this paper we have presented only a brief review of the problem of erosion along the Scarborough shoreline. Currently, the area presents the most difficult erosion problem along the Canadian coastline. Undoubtedly, under the overall management of the Metropolitan Toronto and Region Conservation Authority, erosion will be brought under control, probably within the next decade, but it is worth remembering that the cost of remedial work along the Bluffs is more than simply that of public finances. Whilst the engineer and earth scientist may feel a professional satisfaction at seeing erosion brought under control, the progressive loss of many kilometres of well-exposed and important stratigraphic section to various stabilization schemes (Figs. 4 and 15) is a troubling prospect for the geological community and future earth science investigations.

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