Neotectonic Jointing Control on Lake Ontario Shoreline Orientation at Scarborough, Ontario

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SUMMARY

Many parts of the coastline of Lake Ontario and other Great Lakes consist of long linear sections, commonly made up of tall cliffs cut into Pleistocene-aged glacial sediments. Scarborough Bluffs on Lake Ontario east of Toronto is such a shoreline. Study of the orientation of subaerial and subaqueous joints in both Pleistocene-aged sediments and Ordovician-aged bedrock in the Scarborough Bluffs area indicates that joint orientation in the Pleistocene sediments compares closely with that of the Ordovician bedrock. This observation supports the conclusion that it is neotectonic jointing in Pleistocene sediments that controls the orientation of the cliffed shoreline and the associated creeks in the Scarborough Bluffs area.

RÉSUMÉ

De nombreuses portions de la ligne de côte du lac Ontario et d'autres Grands Lacs sont rectilignes, représentant généralement de grandes falaises recoupant des sédiments glaciaires pléistocène. Les Scarborough Bluffs du lac Ontario, à l'est de Toronto, en sont un exemple. L'étude de l'orientation des joints subaériens et subaquatiques, à la fois dans les sédiments pléistocènes et dans les couches ordoviciennes de la région des Scarborough Bluffs, montre que l'orientation des joints dans les sédiments pléistocènes suit de près l'orientation des joints ordoviciens. Cette observation appuie l'hypothèse d'un contrôle néotectonique expliquant l'orientation des lignes de rivage et des criques les recoupant dans les sédiments pléistocènes de la région des Scarborough Bluffs.

INTRODUCTION

It is readily apparent from small-scale maps that many parts of the coastline of Lake Ontario (and other Great Lakes) consist of linear sections many kilometres in length. These sections commonly consist of tall cliffs cut into cohesive Pleistocene glacial sediments, and reflect rapid postglacial erosion of jointed sediments (*e.g.*, Highman and Shakoor, 1998). We have examined one such area of linear shoreline east of Toronto, Scarborough Bluffs, where the coastline is straight for more than 16 km. Previously published work has shown that despite repeated Pleistocene glaciation, a major control on "preglacial" and postglacial river channel orientation in southern Ontario has been neotectonic joints in bedrock. These joints result from the mid-continent stress field; the term "tectonically predesigned" was used by Eyles *et al.* (1997) in describing the drainage system of southern Ontario. This paper extends this morphotectonic model by identifying a well-developed neotectonic control on modern shoreline orientation at Scarborough Bluffs.

SCARBOROUGH BLUFFS

Immediately east of Toronto, the coastline of Lake Ontario is remarkably straight (Fig. 1). The coast is defined, for more than 16 km, by prominent bluffs whose highest points reach some 90 m above the modern lake level. Average rates of retreat of the bluffs are between 0.31 $m \cdot a^{-1}$ and 0.76 $m \cdot a^{-1}$ (Eyles *et al.*, 1985; Nairn and Cowie, 1997). These rates have been maintained since approximately 8500 years ago when the level of early Lake Ontario began to rise after the low Lake Admiralty phase. Because of the high rates of erosion and the occurrence of substantial cliff falls and slides close to residential and commercial property, the economic impact of erosion in this heavily urbanized area is considerable. Correspondingly, there is great interest in understanding erosional mechanisms and slope-forming processes along the Bluffs (*e.g.*, Nairn and Cowie, 1997).

GEOLOGY OF THE BLUFFS

The Lake Ontario basin contains a thick (up to 200 m) sedimentary record dating from the penultimate (Illinoian) glaciation and last interglacial (Sangamon) stage. In turn, these sediments are blanketed by a thick last glaciation (Wisconsinan) succession that is spectacularly exposed in the Scarborough Bluffs. Pleistocene sequences of the Toronto area fill a broad bedrock low, trending northwest-southeast, that connects the bedrock basins now occupied by Lake Ontario and Georgian Bay. This depression was identified by Spencer (1890) as having been cut by the precursor of the modern St. Lawrence River, which, as the "Laurentian River," flowed directly across the Ontario Peninsula from Georgian Bay to Toronto. The so-called "Laurentian Valley" has been filled with Pleistocene sediment.

Exposures along the Scarborough Bluffs provide a window into the infill of the Laurentian Valley. The succession is composed of a lowermost delta body (Scarborough Formation) draped by a glaciolacustrine sediment complex consisting of diamicts (pebbly muds) and intervening deltaic lithofacies (Karrow, 1967). A lower prodelta member of the Scarborough Formation delta, about 30 m thick, is composed of laminated silts and clay. The delta top is some 35 m above the modern lake level at Scarborough. Several relict channels, up to 100 m deep and 1 km broad, are cut into the delta-top and are infilled by a fine-grained diamict with rare clasts (Sunnybrook diamict member). The latter is interbedded with rhythmically laminated silty clays and sandy lithofacies of the deltaic Thorncliffe Formation, which also includes two more diamict members, the Seminary and the Meadowcliffe. Regardless of lithology, strata are extensively fractured (Fig. 2). These fractures locally control the style of erosion, commonly involving substantial slab failures that fall from free-standing cliffs cut across massive diamict facies. The same fractures control groundwater movement and local porewater pressures in the eroding cliffs

(Eyles and Howard, 1988).

POSTGLACIAL EVOLUTION OF SCARBOROUGH BLUFFS

Scarborough Bluffs result from the long-term post-glacial level-rise of Lake Ontario. Current lake level rise at Toronto is about 23 cm every century. This is because former ice thicknesses were greater toward the northeast; thus the rate of rebound at the lake outlet (at Kingston) is more rapidly creating a rise of lake-level at the western end of the basin (*e.g.*, Coakley and Karrow, 1994). The formerly horizontal shoreline terrace and bluffline of Glacial Lake Iroquois, which lie inland of Scarborough Bluffs at elevations of approximately 45 m above the modern lake level (Fig. 1), were cut about 12,000 years ago, and are tilted up to the northeast.

The shoreline of the Scarborough Bluffs is remarkably linear, oriented at N 40°E, with numerous deeply cut creeks and gullies oriented perpendicular to the shoreline. Together, the shore bluffs and creeks form a markedly rectilinear pattern. Prominent well-developed fractures (joints) lie parallel to the faces of tall cliffs located along the shoreline, and to the steep sidewalls of creeks draining to Lake Ontario (Fig. 2). Well-developed joints are also exposed subaqueously offshore on the Lake Ontario wave-cut floor, which has been eroded across the same Pleistocene sediments (Fig. 3).

Traditionally, the close association between joint orientation and cliff faces would be regarded as the result of simple stress-release during rapid erosional retreat of the cliff face. In contrast to this general model, however, the strike of joints in the sediment cliffs at Scarborough Bluffs lies parallel to the regional joint system that occurs both in Pleistocene sediments and in underlying Paleozoic (Ordovician) bedrock (Fig.

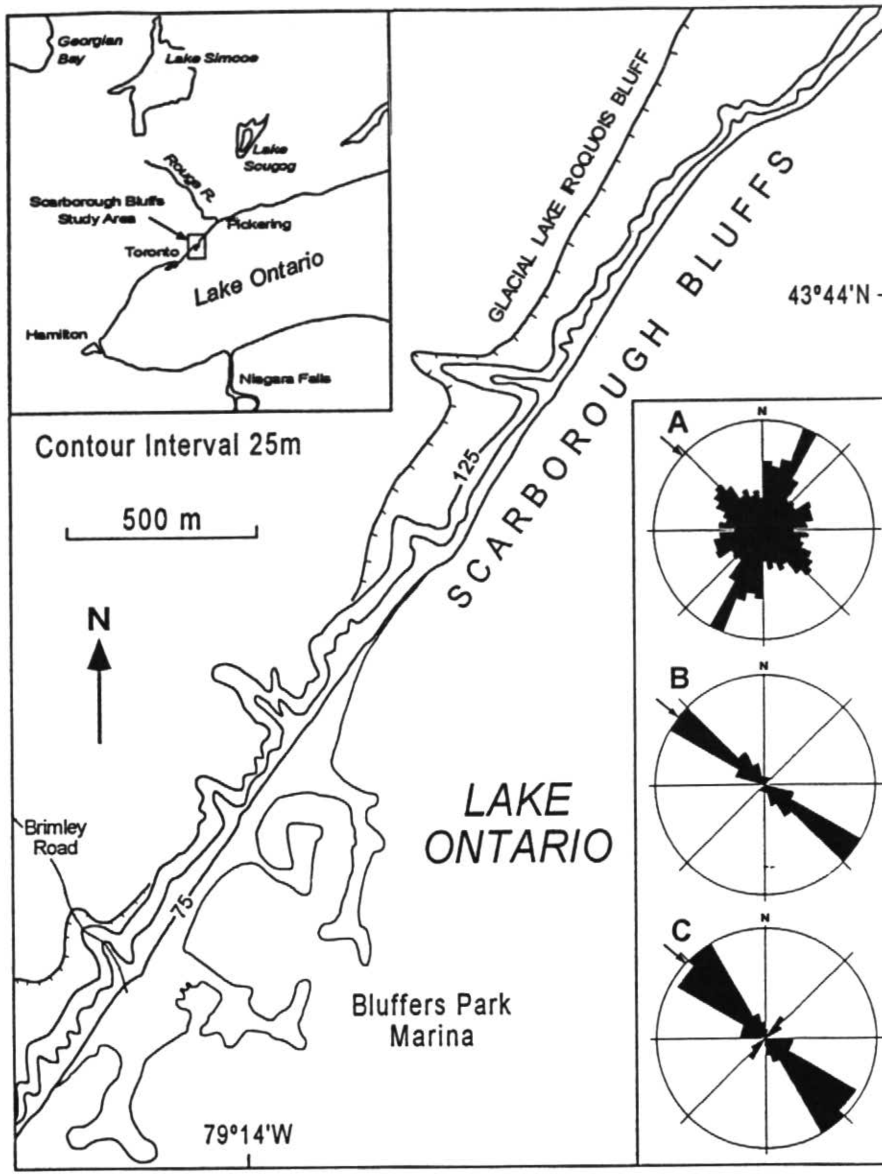

Figure 1 (**top**) Location map of study area with (**A**) strike-rose of co-sets in bedrock (Fig. 4); (**B**) strike-rose of subaqueous joint traces on the floor of Lake Ontario west of Bluffers Park Marina (Fig. 3); and (**C**) strike-rose of joints in Pleistocene sediments in cliffs along Scarborough Bluffs (Fig. 2).

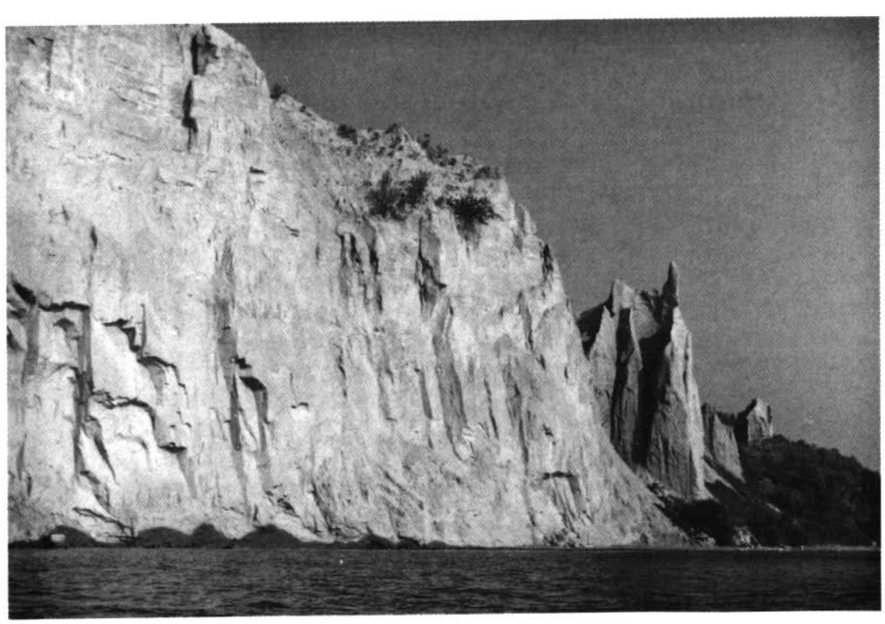

Figure 2 (**bottom**) Prominent joint traces exposed at Bluffers Park along Scarborough Bluffs, Ontario (see Fig. 1 for location). One set of joints can be seen oriented perpendicular to the cliff; the other set of joints forms the smooth planar walls of the cliff. For orientation of these joints see Figure 1C and Table 1.

4). This regional system is the result of mid-plate neotectonic stresses created by the westward drift of the North American plate over the mantle (Scheidegger, 1993; Eyles and Scheidegger, 1995; Eyles *et al.*, 1997; Eyles and Boyce, 1997). The importance of neotectonic joints in Pleistocene sediments, especially overconsolidated tills hitherto regarded as impermeable, has very recently become evident in the Toronto area with respect to intra-till movement of contaminants in ground water (Gerber and Howard, 1996; Eyles and Boyce, 1997), and surface outgassing of Radon222 from shales buried below thick Pleistocene sediments (Je and Eyles, 1998).

METHODS

One objective of our study was to quantitatively test the hypothesis that joints in Pleistocene sediments are neotectonic in origin (*i.e.*, related to those joints developed in underlying bedrock). Second, we wanted to test the assertion that joints exert a structural control on the orientation of the cliffed coastline of Scarborough Bluffs and associated creeks. Joints are clearly evident on and in the floor of Lake Ontario offshore of the Bluffs on the modern wave-cut surface; boulders are trapped within current-widened joint traces on the lake floor (Fig. 3). The orientation of a number of these subaqueous joints was measured from a boat (Fig. 1B) and compared with the orientation of joints exposed in the adjacent coastal cliffs (Fig. 1C) and those in bedrock (Fig. 1A). The nearest bedrock exposures occur in the valley of the Rouge River, and belong to the Middle Ordovician Whitby Formation shale (Rogojina, 1993). Table 1 provides details of the number of joint measurements together with the orientation of the Scarborough Bluffs coastline and associated creeks. Data were evaluated by the statistical method Kohlbeck and Scheidegger (1977, 1985). Table 1 lists the azimuths of the strikes (N>E) for the various groups, together with the errors indicated by ±. Strike roses are given for all data sets (Fig. 1).

RESULTS

Upon inspection of results, it is clear that bluff, lake bottom, and bedrock joints have, fundamentally, the same orientation (Table 1). Joints in bedrock comprise a well-defined co-set forming a rectilinear pattern on strike-rose diagrams (Fig. 1A, Table 1), which is replicated in the orientation of both the coastline features (*e.g.*, Scarborough Bluffs and associated creeks; Fig. 1, Table 1) and of joint co-sets in Pleistocene sediments of the cliffs (Fig. 1C, Table 1). The correspondence between joint co-sets in bedrock and sediment is within 14°. The orientation of lake bottom joints also corresponds closely with that of bedrock joints (Fig. 1B, Table 1).

DISCUSSION

The data presented here indicate a close correspondence between joint orientation in Paleozoic bedrock, those in overlying Pleistocene sediment and the trend of the cliffed shoreline of Lake Ontario and associated cliffs in the Scarborough Bluffs area. This finding is not unexpected. Eyles and Scheidegger (1995) and Eyles *et al.* (1997) showed that neotectonic joints in bedrock exert a major control on the orientation of both modern rivers, cut into Pleistocene sediments, and buried "preglacial" bedrock channels in southern and southwestern Ontario. They

Figure 3 Aerial view of Bluffers Park in September, 1997. Beneath the water level, prominent joints in Pleistocene sediment are expressed as closely spaced black lines perpendicular and parallel to the cliffs to the left of the marina. Joint traces have been widened by waves and accentuated by washed-in cobbles, thus forming dark-coloured lines on the lake floor. The orientation of these joints (Fig. 1B) agrees with the orientation of joints in bedrock (Fig. 1A).

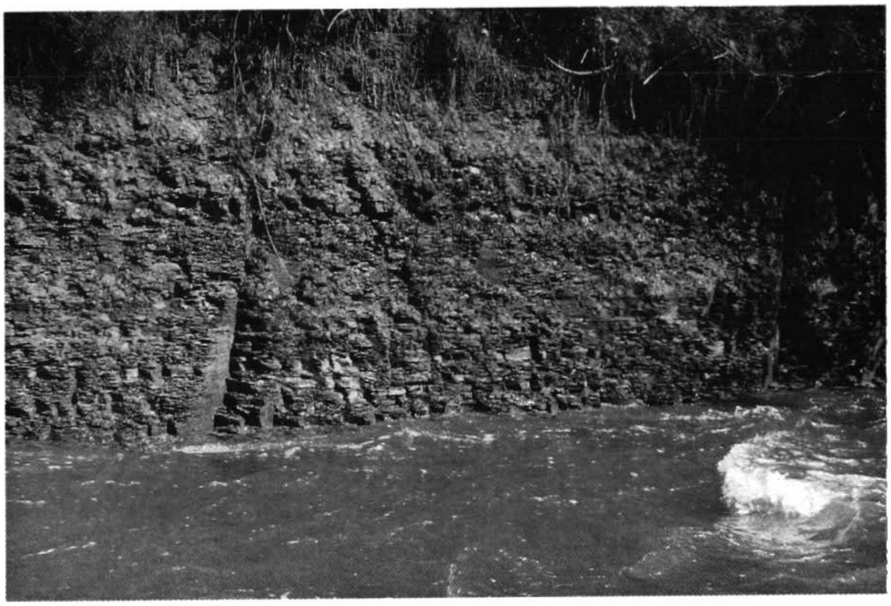

Figure 4 Jointed Whitby Formation shale exposed along the Rouge River Valley (Fig. 1, inset).

Table 1 Orientation of joints, Scarborough Bluffs area, southern Ontario

Location	Number of Measurements	Maximum 1	Maximum 2
Pleistocene sediments			
Bluffs all	42	134±-06	45±-00
Lake bottom	21	126±-06	80±-27
Ordovician bedrock			
Rouge River Valley	602	118±-02	31±-04
Other features			
Valley trend	5	126±-00	—
Shoreline trend	1	—	40±-00

argued that neotectonic joints in Pleistocene sediments have controlled the direction of post-glacial fluvial incision into such sediments, and cited studies in which bedrock joints have been observed passing upward into overlying Pleistocene strata. The specific data presented here from Scarborough confirm this neotectonic model by demonstrating that the linear form and orientation of the Scarborough Bluffs shoreline is joint-controlled. Our data negate a simple "stress-release" model for the origin of such fractures; stress-release is an important process on tall free-standing slopes, but the direction of such jointing is predetermined by neotectonic stresses.

We conclude that neotectonic jointing in Pleistocene sediment is a fundamental control on the orientation of the cliffed shoreline and associated creeks at Scarborough. Other areas of the Great Lakes currently are under investigation to test the broader applicability of this model to other linear, cliffed shorelines cut into Pleistocene sediment. The report of Highman and Shakoor (1998) on the important role of joints in facilitating cliff erosion in Pleistocene sediment elsewhere in the Great Lakes Basin suggests that such study is timely.

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