The Devil Lake pothole (Ontario): Evidence of subglacial fluvial processes
La marmite de Devil Lake (Ontario) : une forme témoignant d'un processus fluvial sous-glaciaire

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Résumé de l'article
Une marmite de 1.93 m de profondeur et d'un diamètre maximal de 1.3 m est située près du sommet d'une crête allongée qui forme un des bras d'un anticinal érodé dans le paragneiss du socle précambrien, dans le sud de l'Ontario. Sa situation en terrain élevé dans une région de plus de 100 m de relief dans la roche en place montre que sa formation ne s'est pas faite par un courant subaérien moderne ou par des cours d'eau qui auraient pu provenir d'un glacier du Pléistocène supérieur en retrait. La topographie du sub-stratum régional déterminée à partir des cartes topographiques et d'un lever acoustique du soubassement des lacs avoisinants présente un modèle d'érosion sous-glaciaire à grande échelle comme celui d'autres sites de la région. La marmite a été formée par un courant sousglaciaire dont l'écoulement était concentré le long du flanc de l'anticinal. Pendant que l'eau s'écoulait autour d'une bosse rocheuse, un vortex s'est formé au droit d'une fracture à la surface rocheuse et a provoqué l'érosion qui devait engendrer la marmite. La configuration des lieux a fait en sorte que les écoulements subséquents suivirent le même chemin. La présence de cette marmite constitue une autre preuve de l'importance des eaux sous-glaciaires comme agents d'érosion et de façonnement du relief sous l'Inlandis laurentidien.
THE DEVIL LAKE POTHOLE (ONTARIO): EVIDENCE OF SUBGLACIAL FLUVIAL PROCESSES

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ABSTRACT  A pothole 1.93 m deep and 1.3 m maximum diameter is located near the crest of a ridge that forms one arm of an eroded anticline in para-gneiss of the Precambrian Shield in southeastern Ontario. It's position on high ground in a region of more than 100 m relief on the bedrock precludes its formation by modern subaerial stream flow or by streams that could have come from the retreating late Pleistocene glacier. The regional bedrock topography determined from topographic maps and a subbottom acoustic survey of nearby lakes exhibits a pattern of large-scale subglacial fluvial erosion reported for other sites in the region. The pothole formed in subglacial flow where discharge was concentrated along the limb of the anticline. As flow streamed around a small rock knob, a vortex was established at a fracture in the rock surface and initiated the erosion of the pothole. This configuration insured that subsequent flows were similarly focused. The occurrence of this pothole is further evidence of the importance of subglacial water as an agent of erosion and the shaping of landscape beneath the Laurentide Ice Sheet.

INTRODUCTION

Evidence mounts that fast-flowing water beneath the Laurentide Ice Sheet significantly shaped landscape by eroding bedrock and creating landforms and landscapes on scales from millimetres to hundreds of kilometres. In the Great Lakes region these features have been documented by, for example, Shaw (1988), Sharpe and Shaw (1989), Gilbert (1990), Shaw and Gilbert (1990), Kor et al. (1991), Gilbert and Shaw (1992, 1994), Brennand and Shaw (1994), Pair (1997), Barnett et al. (1998), and Kor and Cowell (1998). This paper describes a large pothole on a ridge crest in southeastern Ontario in the context of the regional topography, and proposes its origin by subglacial fluvial processes.

SETTING AND METHODS

The pothole is located 173 m a.s.l. (± 0.5 m determined by altimetry) south of Devil Lake (Figs. 1 and 2) on the northern border of Frontenac Provincial Park. The ridge on which it occurs is the eroded remnant of the northern arm of a prominent northeasterly trending anticline (Fig. 1) in the Frontenac Axis of Precambrian Grenville Supergroup metasedimentary rocks, consisting mainly of para-gneiss and related rocks (Kingston et al., 1985). The bedrock

*RÉSUMÉ  La marmite de Devil Lake (Ontario) : une forme témoignant d’un processus fluviatile sous-glaciaire. Une marmite de 1,93 m de profondeur et d’un diamètre maximal de 1,3 m est située près du sommet d’une crête allongée qui forme un des bras d’un anticlinal érodé dans le paragneiss du socle précambrien, dans le sud de l’Ontario. Sa situation en terrain élevé dans une région de plus de 100 m de relief dans la roche en place montre que sa formation ne s’est pas faite par un courant subaérien moderne ou par des cours d’eau qui auraient pu provenir d’un glacier du Pléistocène supérieur en retrait. La topographie du substratum régional déterminée à partir des cartes topographiques et d’un lever acoustique du soubassement des lacs avoisinants présente un modèle d’érosion sous-glaciaire à grande échelle comme celui d’autres sites de la région. La marmite a été formée par un courant sousglaciaire dont l’écoulement était concentré le long du flanc de l’anticlinal. Pendant que l’eau s’écoulait autour d’une bosse rocheuse, un vortex s’est formé au droit d’une fracture à la surface rocheuse et a provoqué l’érosion qui devait engendrer la marmite. La configuration des lieux a fait en sorte que les écoulements subséquents suivaient le même chemin. La présence de cette marmite constitue une autre preuve de l’importance des eaux sous-glaciaires comme agents d’érosion et de façonnement du relief sous l’Inlandsis laurentidien. Through most of the region is discontinuously covered by a veneer of till less than 1 m thick except in small depressions where up to several metres may be found (Kettles et al., 1992). In small lakes, bogs and poorly drained areas (dark shading on Fig. 2) about 1-5 m of Holocene organic muck have accumulated. Except in these areas, the topography determined from the National Topographic Survey 1:50 000 map 31 C/9 (Fig. 2) approximates the bedrock surface on land.

In order to assess the regional bedrock topography beneath the large lakes, subbottom acoustic surveys were conducted on Devil Lake with a 3.5 kHz subbottom profiling system and on Big Clear Lake with a 50 kHz echo sounder. Positions were determined by GPS transcribed to the analogue record at 1 minute intervals. Penetration to the surface interpreted as bedrock was obtained almost everywhere beneath the lake floors (Fig. 3). The surface shown in Figure 2 was contoured by hand from depths determined on transects 50-100 m apart. The velocity of sound in the sediment (a and b in Fig. 3) was assumed to be as in water (1460 m/s).

The topography in the immediate vicinity of the pothole was determined with a surveying level and chain (Fig. 4) and the surface features at the pothole were sketched (Fig. 5).
The shape in plan of the pothole was mapped with a small plane table placed in the pothole at the elevations below the rim indicated in Figure 6. Vertical spacing of measured sections was determined by the configuration of the legs beneath the plane table in the confined space of the pothole. A plumb line was used to centre the table over the deepest point in the pothole, 1.93 m below the north rim and radials were measured at 6° increments from the centre. Thus, each section in Figure 6 is correctly placed in relation to those above and below.

RESULTS AND DISCUSSION

Most remarkable is the location of the pothole on the crest of a ridge. Many potholes are described in the literature but most are along past or present river courses or coasts (e.g. McKellar, 1890) where their origin is easily related to recognizable patterns in the flow in streams or waves. So-called “glacial potholes” on upland surfaces, of which many have been reported (e.g. Upham, 1900) were early-on ascribed to the near vertical movement of supraglacial and englacial water to the bed of the glacier (Elston, 1917; Osborn, 1900). This idea was questioned more than a half century ago (Alexander, 1932; Doll, 1937), and erosion by subglacial meltwater has been invoked for glacial potholes in Scandinavia (Ericsson et al., 1982) and eastern Canada (Sharpe and Shaw, 1989; Kor et al., 1991; Shaw, 1996).

REGIONAL EROSIONAL PATTERNS

The location of the Devil Lake pothole on a ridge crest precludes its formation by stream flow. This paper attempts to show that it was created by subglacial fluvial processes as part of a regional pattern of erosion typical of the subglacial fluvial environment described elsewhere.

Although the landscape of southeastern Ontario is subdued, local elements of relief are important in understanding glacial processes and the origin of landforms (Gilbert, 1990;
FIGURE 2. Site map of the Devil Lake pothole (arrow). Contours on land at 10 m intervals a.s.l. are from National Topographic Survey map 31 C/9 and represent approximately the bedrock surface. Contours under Devil (131 m a.s.l.) and Big Clear (156 m a.s.l.) lakes (lightly shaded) are of the bedrock surface also at 10 m intervals a.s.l. as determined from acoustic survey with 3.5 kHz subbottom profiling equipment and 50 kHz echo sounding. Ponds, bogs and small lakes not surveyed are darkly shaded. Dashed line shows the position of the transect shown in Figure 3. Positions are UTM grid in Zone 18 3_000E 49_000N.

FIGURE 3. A 3.5 kHz acoustic profile from south (at left) to north showing the bedrock surface beneath the lake mapped in Figure 2. The features are interpreted as (a) Holocene sediment fill, (b) conformable late Pleistocene glacial or ice-proximal sediment, and (c) bedrock. The dashed line in Figure 2 locates the profile.

Profil acoustique à 3,5 kHz du sud (à gauche) vers le nord montrant la surface du substratum sous le lac cartographié à la figure 2. Les éléments sont interprétés comme étant (a) un remplissage de sédiments de l’Holocène, (b) un sédiment glaciaire ou de proximité glaciaire conforme du Pléistocène supérieur et (c) le substratum. Le tireté de la figure 2 donne la localisation.
Shaw and Gilbert, 1990; Gilbert and Shaw, 1992, 1994). Figure 1 shows that an area of higher land referred to as Westport Mountain with elevations in excess of 200 m a.s.l. lies north of a major fault scarp along the north shore of Upper Rideau Lake. Palaeozoic limestone forms a lower surface to the north-east toward the Ottawa Valley and extends west to just north of the study area (Fig. 1). The regional slope in the Precambrian rocks of the study area is to the southeast from areas having elevations in excess of 190 m north and west of the pothole site to 100-130 m in the southeastern part of Figure 1.

This pattern appears to have influenced ice flow, directing west southwesterly flow (230-255°) in the vicinity of Upper Rideau Lake (Kettles et al., 1992) to a more south southwest course at the study site (Fig. 1). The anticline with its axis at 225° diverted flow; striations on the southeastern arm are at 210°, while at the pothole on the northwestern limb they are at 245° (Figs. 1 and 5).

This pattern of flow corresponds with the direction of subglacial water flow proposed during the Ontarian event by Shaw and Gilbert (1990). It is probable that subglacial meltwater discharges would also have been locally diverted southward and concentrated by the somewhat higher land to the north of the study site. Further, the anticlines would themselves concentrate flow, especially into the syncline between them, representing the same type of concentration of flow described by Gilbert and Shaw (1994) as creating lakes at the escarpment that marks the limit of Palaeozoic limestones to the south of the study site.

The bedrock topography in the vicinity of the study site (Fig. 2) reflects both the geometry of the metasedimentary rocks in the anticline and the patterns of subglacial fluvial erosion that have been documented elsewhere. The bedrock surface is below 60 m a.s.l. at several places in Devil Lake. A complicated pattern of small ridges (Fig. 3) on the floor of the lake also occurs on land above the lake and indicates substantial differential erosion of the layered metasedimentary rocks that form the anticline. More importantly, the surface beneath the lake is deeply eroded, so that a relief of almost 130 m occurs along the former crest of the anticline. This pattern corresponds with the horseshoe-shaped scours that are found in front of and beside crag and tail features at a small scale (Shaw, 1994) and indicates the substantial role of subglacial meltwater. It is contended that this topographic pattern is inconsistent with erosion by glacial ice.

The horseshoe shape of the topographic depression at the south of Devil Lake and of the Big Clear Lake (Fig. 2) is identical to the forms described by Kor et al. (1991) and ascribed to erosion by water (Gilbert, 1990; Gilbert and Shaw, 1992, 1994) at approximately the same scale as reported here. The relief on the bedrock surface exceeds 100 m downstream along the axis of the anticline through Big Clear Lake. Again, this pattern is inconsistent with erosion directly by glacial ice, but represents the action of larger subglacial flows that initially occupied depressions on the bed beneath the glacier, and at peak flows lifted the glacier from its bed (cf. Shaw and Gilbert, 1990; Gilbert and Shaw, 1994).
There is evidence that the pothole developed in two stages. On the northeast side of the pothole is the remnant of part of an elliptical depression, 5-10 cm deep (Fig. 5). Its outer edge forms a sharp crest with the nearly horizontal bedrock surface around and a small secondary crest occurs within part of the depression.

The main pothole developed in this depression, probably as a result of higher velocity flow. The undercut northwest side (Fig. 6) is consistent with the interpretation of a low-angle jet entering along the left and forming a clockwise eddy directed slightly downward to the right. The upper edge forms a sharp crest with the horizontal surface along the north and west sides but is rounded along the east and south where the jet entered the pothole.

The pothole is nearly circular at the top \(D_{\text{max}}/D_N = 1.10\) at 0.45 m, where \(D_{\text{max}}\) is the maximum diameter and \(D_N\) is the greatest dimension normal to \(D_{\text{max}}\), becoming more eccentric with depth \(D_{\text{max}}/D_N = 1.18\) at 0.94 m, and 2.15 at 1.78 m. The shape and depth are characteristic of “vertical” potholes created by thin, high-velocity flows (Zen and Prestegaard, 1994). The pothole is progressively undercut downslope, probably as a result of a fault or fractured bedding plane parallel to the flow direction that becomes apparent near the bottom of the pothole. It is this feature that drains the pothole today, so that water does not accumulate in it. Small spiral flutings are still visible on the sides of the pothole (cf. Alexander, 1932) but they are badly weathered and individual features cannot be traced for more than a few decimetres. Similar spiral forms were observed in potholes in the Great Lakes region (Sharpe and Shaw, 1989; Kor et al., 1991).

The relation of striations, s-forms and glacial sediment to the pothole suggests that the final stage of pothole formation was at the end of glaciation. Downstream of the pothole, the right bank of the channel carries small s-forms and similar weathered forms are found on the horizontal bedrock surface nearby (Fig. 5). Small, poorly preserved striations trending 245° are overlain on these features, but they were not significantly eroded by direct contact with glacial ice. The bottom 0.3 m of the pothole contained a sandy diamicton identical to the thin till over the region (Kettles et al., 1991). All of the fragments larger than 1 cm were angular and showed no evidence of erosion by water. Thus, the sediment was deposited in the pothole probably from the overlying glacial ice after it had been fully formed. The small amount of sediment suggests that the last stage of formation, or at least occupation by subglacial water, was during the final stages of glaciation.

It is probable that water with fine sediment (sand and silt) was the sole mechanism of formation by corrasion of the pothole (cf. Alexander, 1932) and that a large stone tool was not required; none was found in the pothole. A clockwise rotating vortex transferred momentum to depth. Mass transport of relatively small amounts of water occurred around the sides, as evidenced by the spirals there, with a relatively weak rising current in the centre. This focused energy on the sides of the pothole to depth, and transported the eroded rock particles upward and out of the pothole near the axis of rotation (Alexander, 1932).
The time taken to create the pothole is unknown. It is certainly not large (volume, 2.32 m$^3$) in comparison to the biggest reported (Upham, 1900; Elston, 1917) which are up to several tens of metres in diameter and depth. Lougee (1946) indicated that an almost 2-m diameter pothole formed in gneiss was created in the short time of 6-13 years. Rates of erosion from fluid stress alone indicate that centimetres of erosion may occur in a few hours in a variety of rock types (Houghton et al., 1978). The flow of water draining reservoirs in the Laurentide Ice Sheet was highly episodic (Shoemaker, 1992), as are the jökulhlaups of modern glaciers (Gilbert, 1971; Clague and Mathews, 1973). Individual flow events may have lasted days to weeks and occurred infrequently, perhaps from decades to centuries. The position of the pothole on the flank of the anticline insured that each successive flood created similar conditions of erosion, but it is probable that only a few events were required to create it.

CONCLUSIONS

The Devil Lake pothole provides evidence of subglacial fluvial erosion along ridge crests beneath the Laurentide Ice Sheet in southeastern Ontario. It was created as part of a regional flow pattern that deeply eroded a prominent anticline-syncline complex in the Precambrian rocks of the Frontenac Axis of the Canadian Shield. Its position on the crest of a ridge precludes formation in an existing river. It is also not possible that a subaerial stream existed at this location due to configuration of the ice sheet during deglaciation. At least one, but probably a number of subglacial flow events were diverted by the anticline, eroding it deeply in the present basins of Devil and Big Clear lakes to features similar in form to the smaller scale erosional marks on the bedrock surface elsewhere in the region, and comparable in scale to the larger features reported from the same region. Flow diverted along the flanks of the anticline was locally concentrated and accelerated to create the pothole.

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