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Bedrock erosional features and landforms, Cantley, Québec: GAC-MAC field trip, May 28, 2011

David R. Sharpe, Geological Survey of Canada

Abstract

Several erosional forms on bedrock at Cantley, Quebec, differ from well-known glacial abrasion forms. The forms consist of obstacle marks, hollows, depressions, and channels, which are defined by sharp rims, smooth inner surfaces, divergent flow features, and remnant ridges. These forms are found on lee, lateral, and overhung rock surfaces. This assemblage of features is best explained by differential erosion produced by separation eddies along lines of flow reattachment. Rapid, sediment-laden, turbulent, subglacial melt-water flows likely produced the forms by corrasion and cavitation erosion.

Ice-abrasion forms, such as striations, and such plucked forms as gouges and crescentic fractures are also present at the Cantley site. Pitted forms, polishing, and carbonate precipitate are also found. The occurrence of abrasion, pitting, polishing, and lee-side carbonate precipitate with meltwater forms suggests that the meltwater flows were subglacial. Decoupling of abrading ice from its bed temporarily suspended glacial abrasion, whereas reattachment of ice to the bed may have led to the rounding of sharp edges and the production of striations superposed on the glaciofluvial forms.

The association of forms produced both by glaciofluvial erosion and ice abrasion suggests that the glacier was alternately lifted from, and reattached to, the bed during periodic subglacial floods. These floods may have affected the dynamics of the ice sheet, and depositional sequences related to high-energy meltwater outbursts probably were laid down in adjacent basins.

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Stop 1: Cantley bedrock erosional forms (s-forms)

David Sharpe, Geological Survey of Canada

Location: Cantley Quebec, NTS 31G/12, UTM 18T 438721E 5048793N; 45̊ 35' N, 75̊ 47' W. Parking is in front of a site gate on the west side of Highway 307 (Fig. 1). The quarry is owned by Les Entreprises Vetel Ltée; access is at your own risk after writing to the owner.

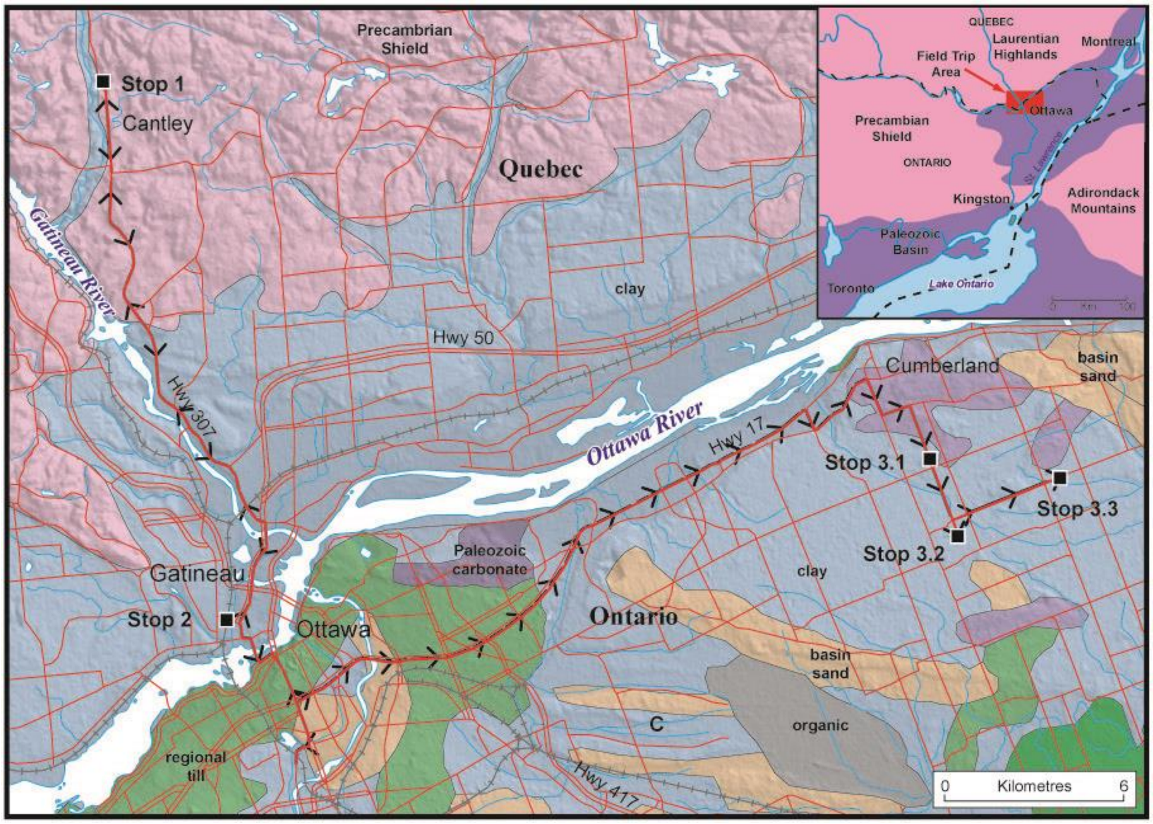

Figure 1 Geology and digital terrain model of the Ottawa area showing fieldtrip stops and route. Inset provides setting of eastern Great Lakes. Stops 2 and 3 are optional and are not reported in this guide

Purpose

The purpose of this stop is to draw attention to the significance and implications of erosion in glaciated terrain. Bedrock exposures within the quarry display subglacial erosional forms that are inferred to be mainly cut by powerful subglacial meltwater flow (Sharpe and Shaw, 1989) within a tributary valley of the Gatineau River (Fig. 1).

Description of site

Bedrock within the quarry consists of Precambrian marble containing resistant granitic or volcanic clasts. The studied outcrop is streamlined parallel to valley orientation and to regional ~ north-south ice flow (Fig. 2). This site was deglaciated prior to 12 000 BP, but until recently, the described features were covered with gravel, sand, and mud deposited rapidly on subaqueous fans formed at the margin of the Champlain Sea (e.g. Rust, 1988; Sharpe, 1988), and below a marine limit of ~ 200 m asl.

Similar erosional forms occur on other outcrops in this poorly-exposed valley. Sculpted forms as observed on the bedrock surface at this site diminish at higher elevation on adjacent outcrops. At the north end of the Cantley site, a 15 m thick sequence of glaciomarine sediments overlie the site and consist of a fining upwards sequence of sandy gravel and bedded sand overlain by silt and laminated clay.

Figure 2 Photograph of major outcrops at the Cantley rock quarry, Stop 1. R is rock drumlin, RR is remnant ridge. Outcrop forms are oriented parallel to the valley (~N-S) and in alignment with flow directions on small features in the quarry. See person for scale.

Erosion forms

Forms range in size from centimeter-scale striations and rat-tails, to meter-scale obstacle marks, to forms the size of the outcrop, 50-100 m long, 5-10 m high (Fig. 2), and perhaps larger north and south of the area.

Striations and rat-tails

Portions of the rock surface are planed-off and striated, such that the granitic and volcanic inclusions lie flush with the surface of the surrounding marble. Small rat-tails are present in addition to striations. Rat-tails are positive forms and indicate differential erosion of the surrounding rock surface, rather than just erosion of striations by a tool held in ice.

Obstacle marks and sichelwannen

The most common and distinctive erosion forms at the site are obstacle marks (Fig. 3), which have ridges in the lee of obstacles (Allen, 1982). These forms consist of a proximal, crescentic furrow wrapped around an upstanding obstacle, or resistant bedrock clast (Fig. 3 b). The proximal furrow commonly has a sharp leading margin. The arms of the crescentic furrow extend downflow in a pair of furrows that become shallower and wider downflow (Fig. 3a, b).

The furrows are often smooth or less striated than adjacent surfaces outside the furrow (Fig 3a), and they can contain divergent flow features (Fig. 3b). Furrows also extend far downflow (Fig. 3c) to form longitudinal forms (Kor et al., 1991). Remnant ridges, which form behind the obstacle and between the furrows, may occur at several scales (compare Fig. 3a, c). An element (F; Fig. 3c), divergent from main flow, indicates vortex flow in the upflow furrow.

Other observed sculpted forms occur without obstacles; they have been called sichelwannen (Ljugner, 1930) or crescentic scours (Dahl, 1965). These are now termed s-forms (Kor et al., 1991) and consist of transverse elements with furrows extending downflow around a central medial ridge (Fig. 2). At this scale, the remnant medial ridges can be considered to be rock drumlins (Fig. 2). A smaller, mussel-shaped transverse form (muschelbruch) occurs with sharp margins but without a medial ridge (see M, Fig. 3a).

Channels or Cavettos and Potholes

Furrows that extend down flow (Fig. 3c) as longitudinal forms result in channels or cavettos (Dahl, 1965). They occur on vertical rock faces either as elongate troughs, or, as winding channels with tight curves (Fig. 4). Cavettos are commonly meters long and centimeters to meters deep, and they may crosscut other features (Fig. 4b). They may have vertical segments similar to truncated potholes (Gjessing, 1967). Vertical segments (Fig. 4c) are considered to be non-directional forms (Kor et al., 1991). At this site, rat-tails indicate that the eroding flow was only upward, unlike classical potholes, in which flow at the outside of the form is downward. Vertical flux implies flow under a very high hydrostatic pressure gradient.

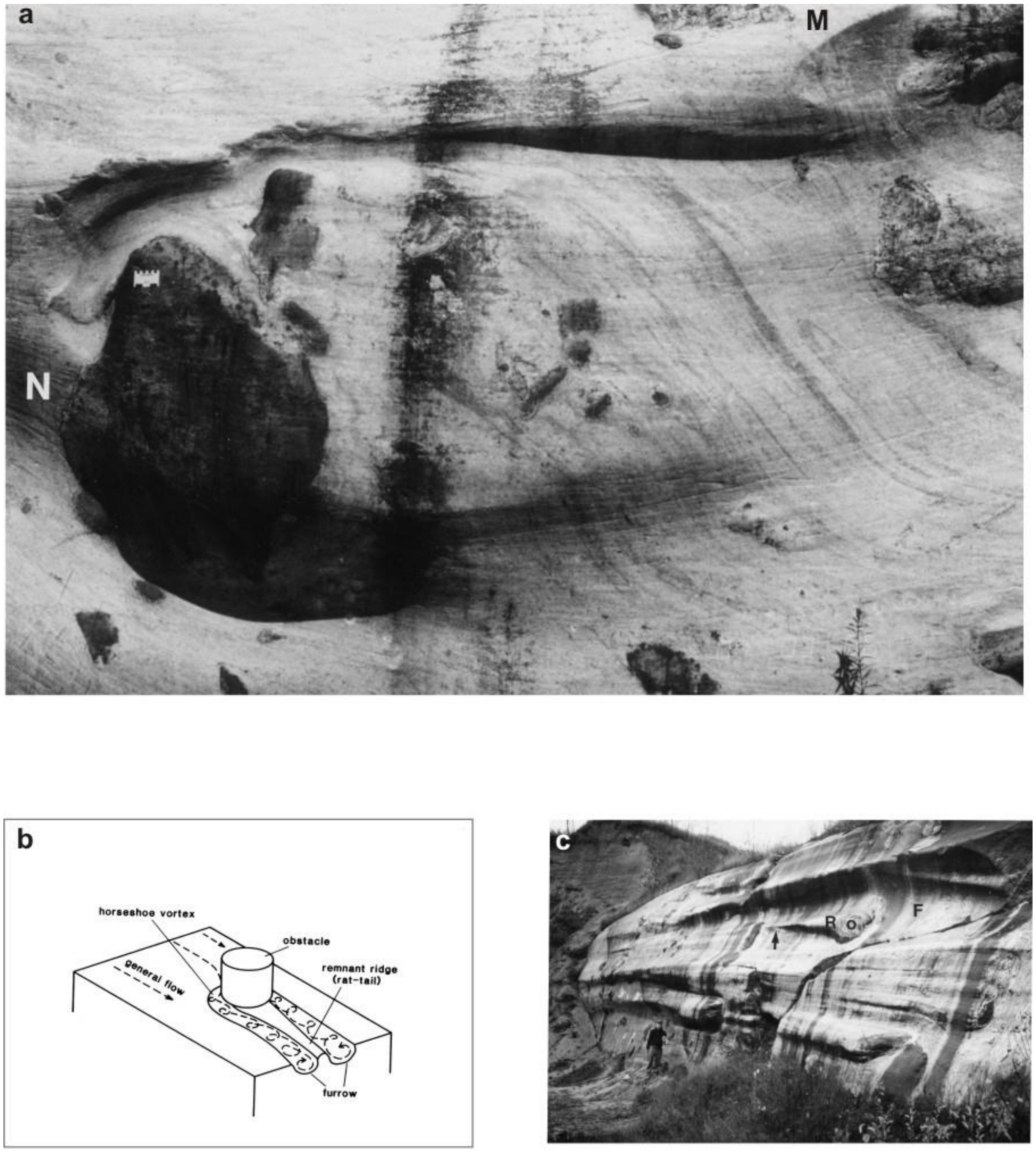

Figure 3 Obstacle marks (transverse s-forms): a) Sculpted forms diverge around dark inclusion (see 8 cm scale card at top) or obstacle within marble, set on a vertical rock face. Sculpted arms, or furrows, become wider and shallower downflow to the right, leaving a remnant ridge in the lee of the obstacle. Note striation or lineation, and rat-tails on the rock surface. Flow left to right. b) Conceptual process model of obstacle mark formation under turbulent flow (Allen, 1971). c) A number of obstacle marks (O) occur on rock surface, some with large furrows (F) upflow of an obstacle and well-defined tapered remnant ridges (R). Note large, divergent rat-tail within the upflow furrow. Flow right to left parallel to outcrop orientation. Note Henri Richard for scale, lower left.

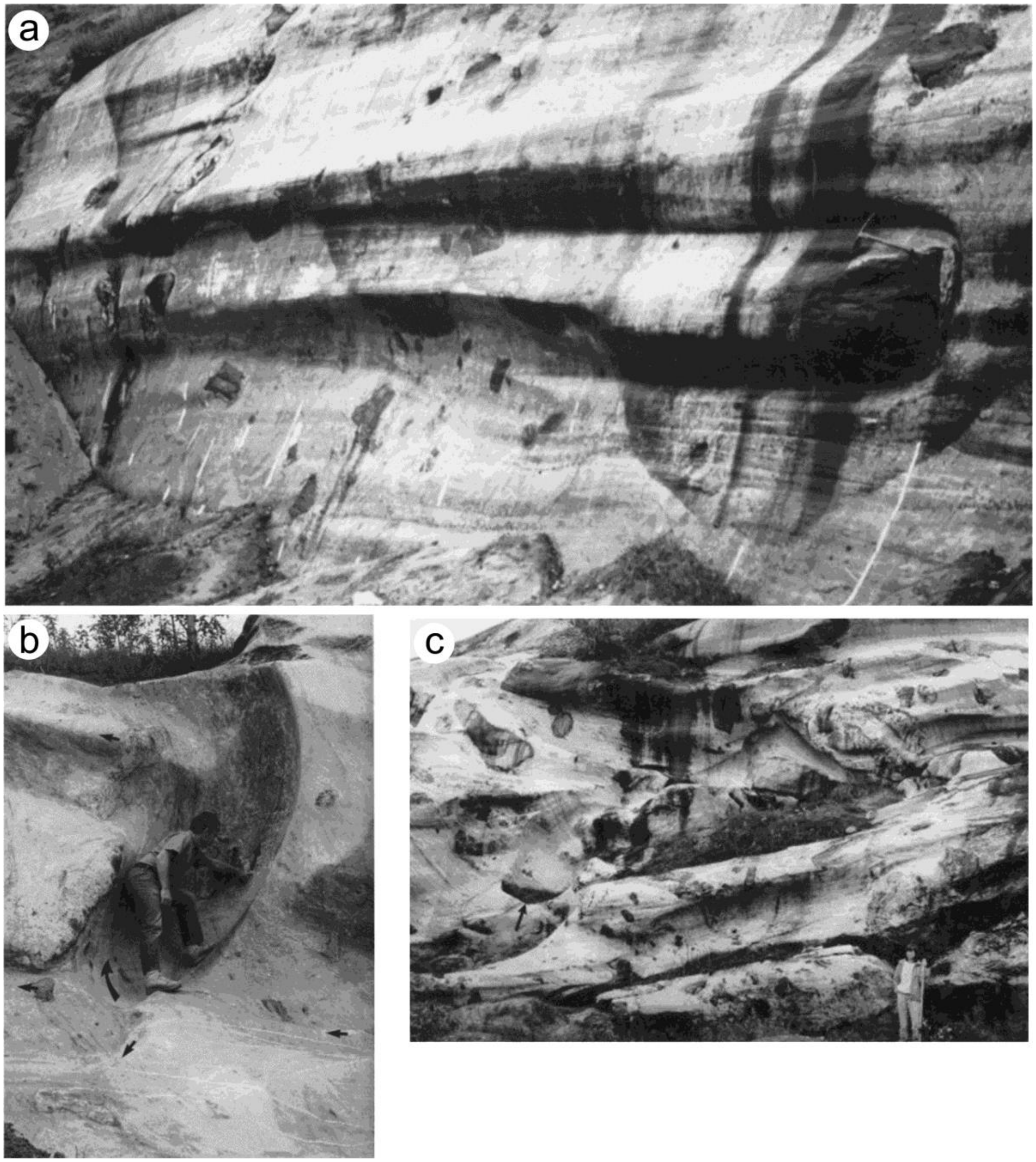

Figure 4 Furrows, cavettos and potholes: a) Poorly-developed upflow furrow extends to lengthy longitudinal furrows (~10 m) and remnant ridge. Flow right to left parallel to outcrop orientation. b) Cavetto or channel-like form with vertical orientation. Flow is upwards as indicated by rat-tails (arrow). This vertical structure had flow directed upwards rather than downward as in potholes. This indicates very high piezometric heads in the subglacial water system. c) Complex pattern of longitudinal s-forms; furrows and cavettos. Flow left to right parallel to outcrop orientation. Note person lower right for scale.

Other features

Interior surfaces of many s-forms are scored by light scratches (tool marks?). The scratches are short and are generally aligned with the direction of flow indicated by the divergent axes of troughs and associated rat-tails (Fig. 5). They also diverge, as the sculpted form becomes wider downflow.

Carbonate precipitate is found on polished surfaces in places, particularly in the lee of obstacles, and on remnant ridges (Fig. 5a). The precipitate likely formed in the late stages of flow (lee side occurrence) and as sediments started to bury the landforms.

Pitting can occur on the upflow side of obstacles with remnant ridges (Fig. 5b). This appears to be incipient development of upflow furrows, perhaps as an emerging rock ridge is exposed to accelerated erosion.

Figure 5 Other erosional features: a) Short, light scratches occur in alignment with the axes of furrows (f) and associated remnant ridge surfaces. Carbonate precipitate (C) is also found on polished surfaces in places, particularly in the lee of obstacles (O) and on remnant ridges (see 8 cm card). b) Pitting occurs on the upflow side of an obstacle with a remnant ridge (see also Fig. 5b). Note striations adorn this surface and form at slight cross-cutting angles. c) Striations, set at an oblique angle, occur on top of transverse s-form (sichelwannen). This appears to record the glacier sole re-attaching to the sculpted rock surface.

Cross-cutting forms

There are many cross-cut relationships involving striations and sculpted forms on Cantley outcrops (Fig. 3c, 4b, c, 5c). For example, striations occur as ornamentations, set at an oblique angle, on top of a transverse s-form (sichelwannen). In some forms, rat-tails readily show divergent flow within s-forms (Fig. 4c).

Interpretation

Glacial Abrasion

From the evidence of striations on the surfaces of some sculpted marks, it is concluded that the erosional forms at Cantley were created subglacially. Striations and planed-off inclusions indicate glacial abrasion. Such abrasive planning is attributed to erosion by debris in the bed of flowing glacial ice (Hallet, 1981). There are fewer planed erosion surfaces than surfaces carrying sculpted forms (s-forms). S-forms, in contrast to striations, likely relate to differential erosion expected in flow systems with secondary, turbulent structures (Allen, 1971). Alternatively, the possibility of glacial formation of obstacle marks considers laminar streaming of debris-rich glacial ice around an obstacle (Boulton, 1974). In addition, Gjessing (1965) proposed that, although some s-forms result from fluvial erosion, others are a product of erosion by a subglacial slurry of saturated till. Others suggest that the saturated till, as a deforming bed, was responsible for erosion of streamlined rock forms (e.g. O'Cofaigh et al., 2005).

Corrasion in turbulent separated flow

Cantley obstacle marks, and other transverse s-forms, are thought to result from glaciofluvial processes (Sharpe and Shaw, 1989; Kor et. al., 1991; Munro-Stasiuk et al., 2005). S-forms associated with obstacles are likely formed by flow separation and horseshoe vortices (Fig. 3c), resulting from a vertical pressure gradient generated at the up stream face of the obstacle in turbulent flow (Shaw, 1988; 1994). This gradient sets up secondary flow and a pair of oppositely rotating vortices (Fig. 3c). These secondary flows reattached to the bed where high velocity fluid approached at a high angle and caused maximum erosion (Allen, 1971, 1982). The crescentic furrow cut around the leading side of the obstacle and the paired furrows extending downflow are likely products of a horseshoe vortex. These vortices expanded rapidly and thus, became reduced in intensity and erosional power downstream. As a consequence, the furrows become broader and shallower downflow (Fig. 3b, c), and, rat tails, the remnant (rock) ridges between the furrows, becomes narrower and lower. Sichelwannen similarly relate to flow separation and horseshoe vortices (Kor et al., 1991), whereas muschelbruch (Fig. 3a, b) likely relate to impingement of low-angle vortices on the bed (Shaw, 1988).

Some s-forms that are oblique to the general flow direction indicated by a longitudinal element are preserved due to their protected location within a furrow. Most appear to represent secondary flows related to vortices within a primary flow. This type of mechanical erosion at Cantley is considered to be glaciofluvial corrasion and can occur by direct fluid stressing, or, it can be related to erosion by tools carried in flowing water (Allen, 1982).

The smaller scale forms described are also identical to some sculpted fluvial forms in terrain subject to flooding in Australia (Baker and Pickup, 1986). Some larger forms are similar to forms identified within the Channeled Scablands of Washington State (Bretz, 1925; Baker, 1978). These comparisons support the interpretation of formation by water erosion. Allen (1971, 1982) also verified by way of flume experiments that erosional forms such as these found at Cantley can be produced by high-velocity, separated, turbulent fluid flow.

Cavitation

Cavitation is the rapid formation and collapse of bubbles due to local pressure gradients in turbulent flow. It becomes a viable erosion process where turbulent flow has high enough velocity (~5-10 m/s; Hjulstrom, 1935; Richardson and Carling, 2005). Damaging shock waves and violent jets of water score turbine blades, and can loosen grains in rocks, pit massive rocks, such as may be inferred in places at Cantley.

Dissolution features

There is some evidence of dissolution of Precambrian marble at Cantley. There are, however, few dissolution features, and carbonate precipitation indicates a non-dissolution regime following main subglacial erosion. It does not appear to be a dominant process, despite the suggestion of Hillaire-Marcel (2005) that the site 'represents the mixed influence of mechanical abrasion by basal ice and of dissolution features due to high pressure subglacial water channeling'. Dissolution features probably relate to minor post-glacial modification of common sculpted forms that has taken place on marble surfaces following removal of sand and gravel from the quarry rock surface in recent years.

Discussion

The outcrops at Cantley display s-forms (e.g. obstacle marks, furrows, and cavettos) with sharp rims, divergent flow features, and remnant ridges. They also show ice abrasion forms, striations, and plucked forms such as crescentic fractures. The occurrence of abrasion, pitting, polishing, and carbonate precipitate with meltwater forms suggests that the meltwater flows were subglacial. Lifting of ice from its bed by fast-flowing meltwater suspended glacial abrasion. When ice settled back on the bed, as the meltwater flow subsided, abrasion resumed, rounding sharp edges and lightly striating rock faces, in places at oblique directions.

The association of forms produced both by glaciofluvial erosion and ice abrasion suggests that the glacier was lifted from and let down on the bed during subglacial floods. The assemblage of sculpted features at Cantley is best explained by differential erosion produced by strong vortices. Rapid, sediment-laden, turbulent, subglacial meltwater flows likely produced most forms by corrasion and cavitation erosion (Sharpe and Shaw, 1989). Depositional sequences (sand and gravel) related to these high-energy meltwater outbursts were probably deposited on subaqueous fans in the adjacent Champlain Sea basin (e.g. Rust, 1988; Sharpe, 1988; Cummings et al., 2011).

Regional process implications

Water-sculpted erosion forms imply subglacial bed conditions with little frictional resistance in the areas of subglacial meltwater flow at the time of such discharge (Shoemaker, 1992). The large inferred discharge rates also require meltwater storage, likely in subglacial reservoirs (e.g. Alley et al., 2006; Evatt et al., 2006), up-ice from the Cantley site. Such stored subglacial water may have occurred in Hudson Bay or in any bed-roughness element on the scale of 5 km or more (e.g. modern day lake basin) that are found in abundance on the Canadian Shield (Showmaker, 1992). Separation of the glacier from its bed by a subglacial meltwater sheet, as in some Icelandic floods, also involves minimal basal resistance to ice flow (Shoemaker, 1992; 1999), and a flat ice sheet is expected to cover such discharge and storage areas (Wingham et al., 2006). The importance given here to meltwater events correspond to that applied by others to subglacially deforming till beds (e.g. Boulton and Hindmarsh, 1987; O'Cofaigh et al., 2005). Both process models imply low basal shear stresses, a relatively flat ice-sheet profile, and minimum ice volumes for a given ice-sheet radius. It is important to note that, in the melt- water explanation, these conditions may occur even where the substrate is bedrock. The rapid discharge of meltwater interpreted here is expected to have been accompanied by accelerated ice flow, perhaps surging (Kamb et al, 1985), or ice streaming (Bell et al., 2007). If ice-sheet profiles are to be credibly reconstructed, it becomes critical that subglacial meltwater forms be mapped and their timing be assessed (Sharpe, 2005).

Key questions posed during the Cantley field trip stop

1. Are sculpted erosion forms (s-forms) distinguishable from ice flow indicators (striations etc.)?
2. Do s-forms and striations record fundamentally different processes?
3. Should s-forms and related features be mapped and recorded on maps separately from ice flow indicators (striations)?
4. Is it possible that s-forms and ice flow forms record different manifestations of the same event, or closely timed events?
5. If s-forms are present across a region, is it reasonable to assume/ link a regional event(s) as is the case of with striation mapping.
6. If rapid flow events are inferred in this region, are ice streams responsible for erosional and depositional landforms?
7. What are the processes responsible for rapid flow if ice streams operated in this region?
8. Are ice stream and meltwater-flow features identifiable on this landscape?
9. Could ice streams and meltwater floods occur in closely-timed or the same event sequence?
10. Is there sedimentological evidence for a large volume of stored subglacial meltwater present up flow from the Cantley site?
11. If a distal site is invoked (e.g. Hudson Bay) are flow paths visible between Hudson Bay and the Cantley site?
12. What evidence may be assessed to distinguish between sub-glacial or supraglacial meltwater reservoirs and pro-glacial lakes?
13. We have erosional (rock) drumlins at Cantley. Are the drumlins south of the fieldtrip area erosional or depositional? How can we test/ constrain either case?
14. If drumlins south of the fieldtrip area are erosional, how are striations under a sediment drumlin linked to the landform sediment and its orientation?

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