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Glaciated terrain and erosional features related to a proposed regional unconformity in Eastern Ontario

Field trip Guide Book

D. Sharpe, A. Pugin

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David Sharpe and André Pugin

FIELD TRIP GUIDE BOOK

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[1] Cover painting by Juliana McDonald, The Enriched Bread Artists, 951Gladstone Ave., Ottawa, Ontario, K1Y 3E5. She has interpreted Canadian Shield rock formations for many years, see her website: www.julianamcdonald.ca.

Field trip itinerary and trip map (figure 1)

8:30 *Depart Carleton University;* north on Booth Street to Gatineau, rue Montcalm; *proceed via Highway 50 to east Gatineau; north on Highway 307 (Archambault/ Montée de la Source) to Cantley village (intersection St-Andrew); continue north for 5 km to quarry on left hand side of the road). Trip is ~25 km.*

9:00-11:00 Stop 1. ***Cantley erosion forms and glaciomarine sediment***
11:00-11:20 *Return to Ottawa via highways 307 and 50;* right on rue Moncalm, 200 m; then right on rue St-Laurent, 200 m;
11:20-11:40 Stop 2. ***Pothole in the Ottawa River valley***
11:40-12:15 *Return south on rue Montcalm; south on Booth street to Highway 417. Travel east on Highway 417 to Trim Road, east of Orleans. Proceed south to Wilhaven Drive and travel east to O'Toole Road and turn south 400 m.*
12:15-13:30 ***Lunch*** *in Orleans Park if raining; if not proceed to Stop 3.1.*
13:30-16:00 Stop 3. ***Terrain features on the margin of the Champlain Sea plain***

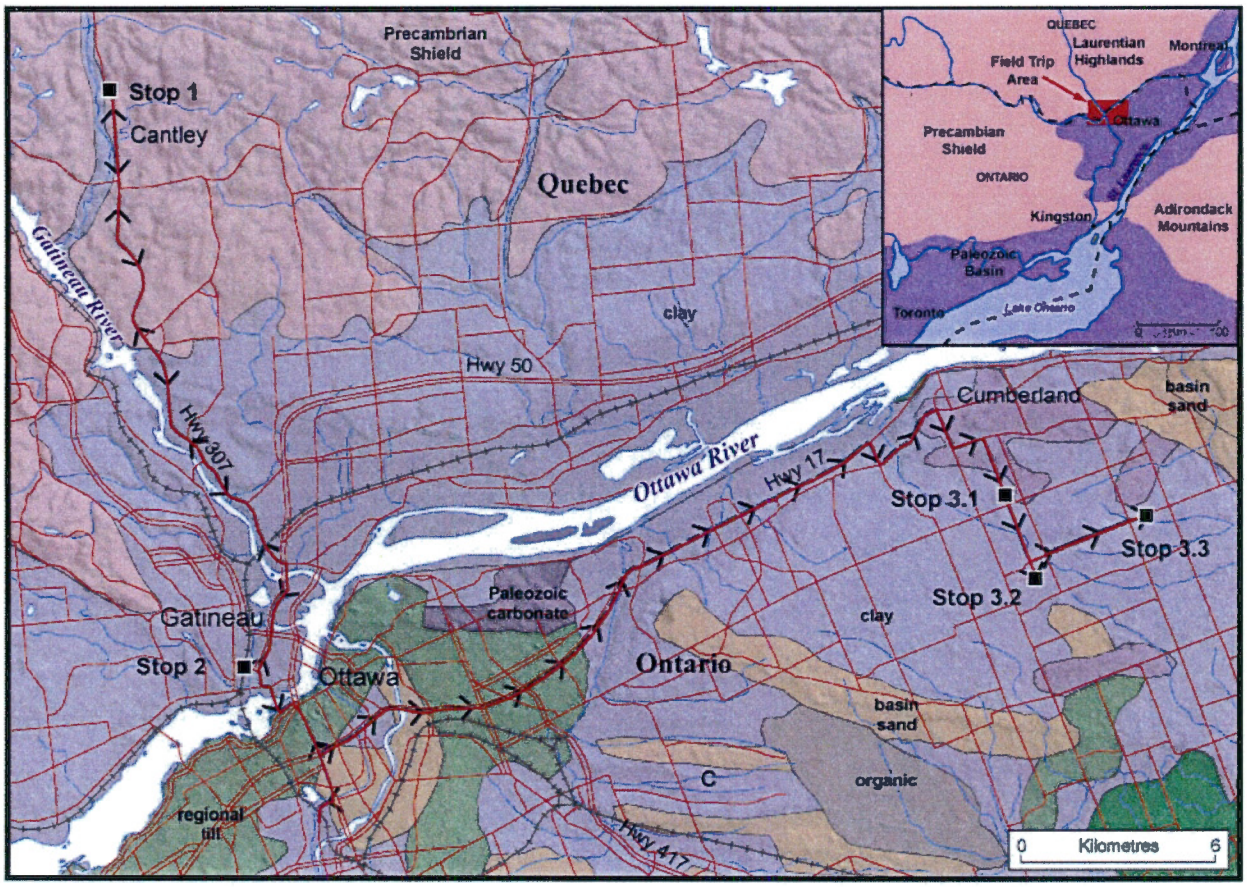


Figure 1. Geology and digital terrain model of the Ottawa area showing fieldtrip stops and route. Inset provides setting of eastern Great Lakes.

Trip overview

Glaciated terrain in the national capital region of Ontario and Quebec reveals key landscape elements and surface-subsurface architecture that are used to identify new elements of a proposed regional unconformity. The erosional surface/unconformity occurs on exposed Grenville marble in the Cantley rock quarry (stop 1) and on sediment and rock surfaces within the Champlain Sea basin (stop 3; Fig. 1). Rock surfaces in the quarry provide striking examples of the effects of erosion on late-glacial landscapes. The quarry also contains poorly-exposed coarse-grained sediments that rest directly on the sculpted quarry floor. These coarse sediments appear to extend further south into the adjacent Champlain Sea Basin and represent subaqueous fans of high-energy glaciofluvial sedimentation.

A younger surface, perhaps superimposed on the regional unconformity, is viewed at stop 2. Stop 3, east of Ottawa (Figs. 1 and 2), reveals a mainly buried erosion surface illustrated by outcrop mapping, reflection seismic survey and drill core analysis. The scoured surface carries a bedrock valley, a number of sediment and rock (?) drumlins with intervening troughs, a boulder lag, and, glaciofluvial sediments resting beneath Champlain Sea mud. This stop also highlights new advances in the acquisition of reflection seismic data for 3D mapping (e.g. Pugin et al., 2007; Pullan et al., 2007). Regional maps present the fieldtrip features in a broader content.

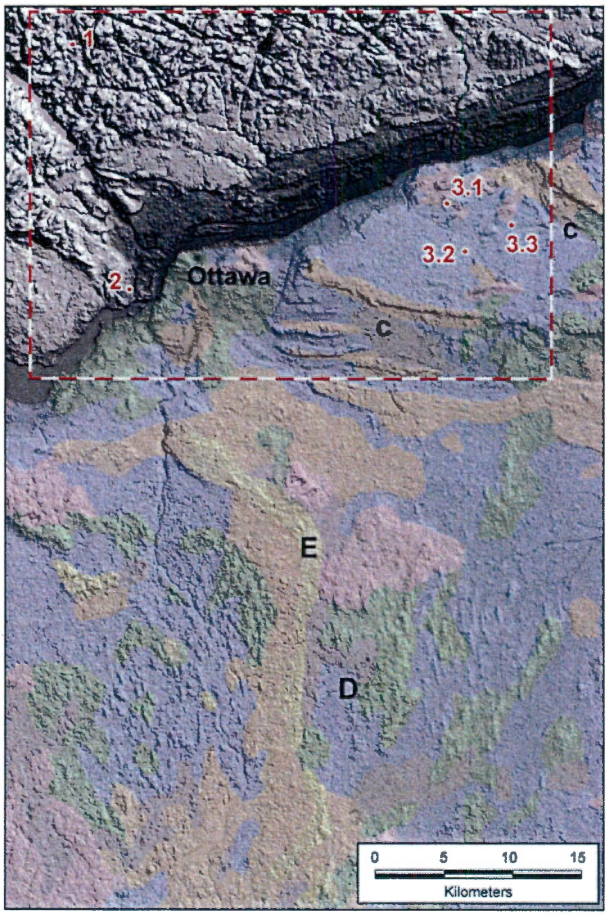


Figure 2. Regional geology (see figure 1 for units), landforms (D is drumlin field; E is esker system), trip stops set on a digital terrain model. Rectangle highlights area of figure 1. Location of stop 3 occurs in an island of the paleo-Ottawa channel defined by incised channels (c).

The examined surface-subsurface terrain features provide evidence for discussion on competing hypotheses for, or against, rapid flow in late-glacial events, whether from ice streaming related to regional-scale sub-ice deformation, and /or from regional-scale subglacial meltwater flow events. The framework for this discussion is set within a list of questions related to: i) description of erosion forms, ii) ability to recognize and map forms across regions, and ii) formative processes.

Hydrogeological significance

Basin analysis research is being carried out in the eastern Ontario portion of the Champlain Sea basin to assess Great Lakes aquifer systems as part of the Groundwater Mapping Program of the Geological Survey of Canada. The research focus is on archetypical aquifer systems particularly in buried valleys, including tunnel channels, and in eskers and stratified moraines in southern Ontario (e.g. Sharpe et al., 2002). Strategic targets for delineating new aquifer systems in such glaciated terrains are depositional settings resting immediately on regional unconformities. These settings, in places, contain coarse-grained sediment deposited after inferred regional outburst flood events eroded a regional unconformity (e.g. Sharpe et al., 2004.). Such new target aquifers have been successfully identified in the Oak Ridges Moraine area and similar settings in southern Ontario (e.g. Desbarats et al 2005; Holysh et al., 2004; Russell et al., 2005; 2006; Sharpe and Russell, 2004; Sharpe et al., 2005; Slattery, 2003). Recently, new water supplies have also been identified in such target aquifers south of stop 2 near Embrun (George Gorrell, personal communication, 2007).

Acknowledgments

This groundwater science is being conducted in partnership with the Ontario Geological Survey, Ontario Ministry of the Environment, South Nation Regional Conservation Authority, Eastern Ontario Water Resources Committee and the University of Ottawa. The geophysical field work was carried out by Sue Pullan, André Pugin, Jim Hunter, Robert Burns, Tim Cartwright, Marten Douma and Ron Good of the Geological Survey of Canada, and, Beth Sargent from the South Nation River Conservation Authority. Drilling and logging of continuous core were carried out by George Gorrell, Don Cummings, Martin Douma, Hazen Russell and Dmitri Ponomarenko. Land access approval was provided by Anne-Marie Chapman and Emil Laurin of the South Nation Conservation Authority. This publication is a contribution of the Earth Science Sector, Geological Survey of Canada, Groundwater Program; part of the Groundwater Inventory, Aquifer Systems in Southern Ontario. Graphic support is appreciated from Mary Clarke, Louis Robertson, and Paul Stacey. The authors appreciate the critical review provided by R. Knight, H.A.R. Russell and J. Shaw.

Regional Geology

The fieldtrip covers highlands of the Canadian Shield and low-relief terrain of the St. Lawrence Lowland, astride the Ottawa River (Fig. 1). Laurentian (Gatineau) highlands consist of Pre-Cambrian rocks of the Grenville Province, which rise 100-200 m above lowland terrain to the south (Fig. 2). The lowlands are part of the Ottawa-Bonnechere graben and are underlain by Paleozoic carbonate and shale with minor clastic rocks of the St Lawrence Lowlands (Fig. 1), which are sporadically exposed across the region. These rocks are extensively faulted within the graben and show considerable variability in outcrop lithology (e.g. Salad Hersi and Dix, 2006). The structurally-controlled basin also displays a number of exposed rock scarps. Lowland terrain is underlain by several glacial and postglacial features (Figs. 1 and 2): a) oriented till uplands, particularly north of Kemptville (D); b) NS-trending esker systems (E); c) Champlain Sea basin and littoral sediments; d) ancestral fluvial channels (C), and e) wetlands (Fig. 2) (e.g., Richard et al., 1974; Gwyn and Thibault, 1975; Gadd, 1980; Fulton, 1987; Gorrell, 1991; Sharpe, 1979).

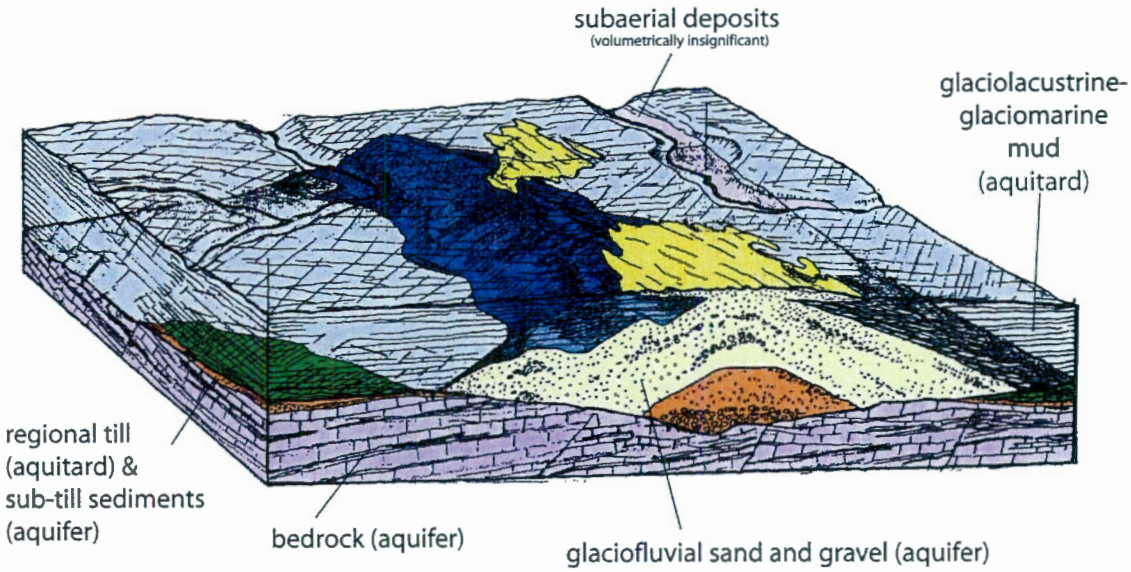


Figure 3. Regional stratigraphic model of the Ottawa area illustrated as a conceptual sketch of esker sediments in the Champlain Sea basin. Drawing is by John Glew, Queen's University.

The area was last glaciated in late Wisconsinan time (~12-25 Ka) and latest ice flow was approximately north to south. Champlain Sea occupied the area from ~12.5 to 10Ka, depositing extensive, thick basin mud. Some bedrock depressions in the region extend below sea level and contain >100 m of fine sediment. Isostatic rebound forced the Champlain Sea eastward during glacial retreat. As the sea regressed, a large northwest to southeast discharge of the proto-Ottawa River eroded several large channels, or incised valleys (C, Fig. 1; Fig, 2), into Champlain Sea mud (Richard et al., 1974).

The stratigraphic succession has been simplified into seven regional units (Figs. 2, 3). i) *Paleozoic bedrock.* ii) *Sub-till sediment* (not shown on map); sand, gravel and mud revealed at Pointe Fortune, directly overlies bedrock (e.g. Veillette and Nixon, 1984). iii) *Regional till*, silty, sand Fort Covington Till, observed in drumlinized uplands and intercepted in some boreholes; forms a regional unit that is locally eroded (Terasmae, 1965; MacClintock and Stewart, 1965; Gwyn and Thibault, 1975; Ross et al., 2006). iv) *Glaciofluvial sediment* is mapped extensively in eskers and may occur laterally as thinner units beneath Champlain Sea sediment (Gorrell, 1991; INTERA, 2005; Chapman et al., 2006). v) *Glaciolacustrine and Glaciomarine* mud, rhythmically-bedded sediment of the Champlain Sea, forms a regional unit that covers glaciofluvial sediment across the region (e.g. Gadd, 1987). vi) *Basin sand,* marine littoral deposits and deltaic sand. vii) *Subaereal deposits;* variable sediment lumped together, including alluvium of proto-Ottawa River, modern alluvium, aeolian dunes, and organics that occur as significant wetlands. These units and several unconformities are discussed in more detail based on work underway on the Vars-Winchester esker system southeast of Ottawa (Cummings and Russell, 2007).

Field Methods

Seismic reflection technique

Landstreamers are efficient means of recording shear-wave reflection data (e.g. Inazaki, 2004, Pugin et al., 2004, 2007). The Geological Survey of Canada has had success in mating the IVI (Industrial Vehicles International, Inc) mini-buggy mini-vib source and an SH-wave landstreamer receiver array (Pugin et al., 2007; Appendix I). This success led to testing SH-wave technology in the very low shear-wave velocity setting of the Champlain Sea sediment (Vs ~150-200 m/s). The landstreamer array consisted of 23 sleds at 0.75m spacing, with 2 horizontal 8 Hz geophones per sled, cross-connected as described in Pugin et al., (2002). The mini-vib (6 seconds sweep, 10 Hz to 100 Hz) produces excellent quality records on both gravel and paved road surfaces. A source spacing of 1.5 m was used, resulting in a bin size CDP spacing of 0.75 m with 12 nominal stack fold. The short spacing of the sleds avoids spatial aliasing of the surface waves, and this yields optimum results when FK-spatial filters are applied. Using these parameters with the landstreamer-mini-vib system, a 3-4 person crew acquired 1-1.5 km of survey line a day. Details of seismic profiling methods are presented in Appendix I.

Continuous core drilling

Seismic facies analysis of glacial sediments is a key technique for subsurface mapping (e.g. Pugin et. al., 1999), and it is being used in the Champlain Sea basin to accurately identify drilling targets (Pugin et al., 2007). Continuous core descriptions were completed so that sediment facies could be directly compared with seismic facies to define sediment architecture.

Field trip stops

STOP 1: Cantley Rock Quarry

Location: Cantley Quebec, NTS 31G/12, UTM 438049; 45 35' N, 75 21' 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.

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 granite or volcanic clasts. The studied outcrop is streamlined parallel to valley orientation and to regional ~NS ice flow (Fig. 4). 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 completely cover the streamlined outcrops but they diminish and disappear with elevation on outcrops adjacent to and above this site. This pattern of erosion and the position of the streamlined outcrop in the valley bottom suggest late flow at least confined to a valley width of several kilometres.

Figure 4. 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 striae and rat-tails, to meter-scale obstacle marks, to forms the size of the outcrop, 50-100 m long, 5-10 m high (Fig. 4), and perhaps larger north and south of the area.

Striation 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 (Fig. 5a). Small rat-tails (Prest, 1983) are present in addition to striations (Fig. 5b, c). Rat-tails are positive forms and indicate differential erosion of the surrounding rock surface (Fig. 5c), rather than the linear erosion of striae by a tool held in ice (Fig. 5a).

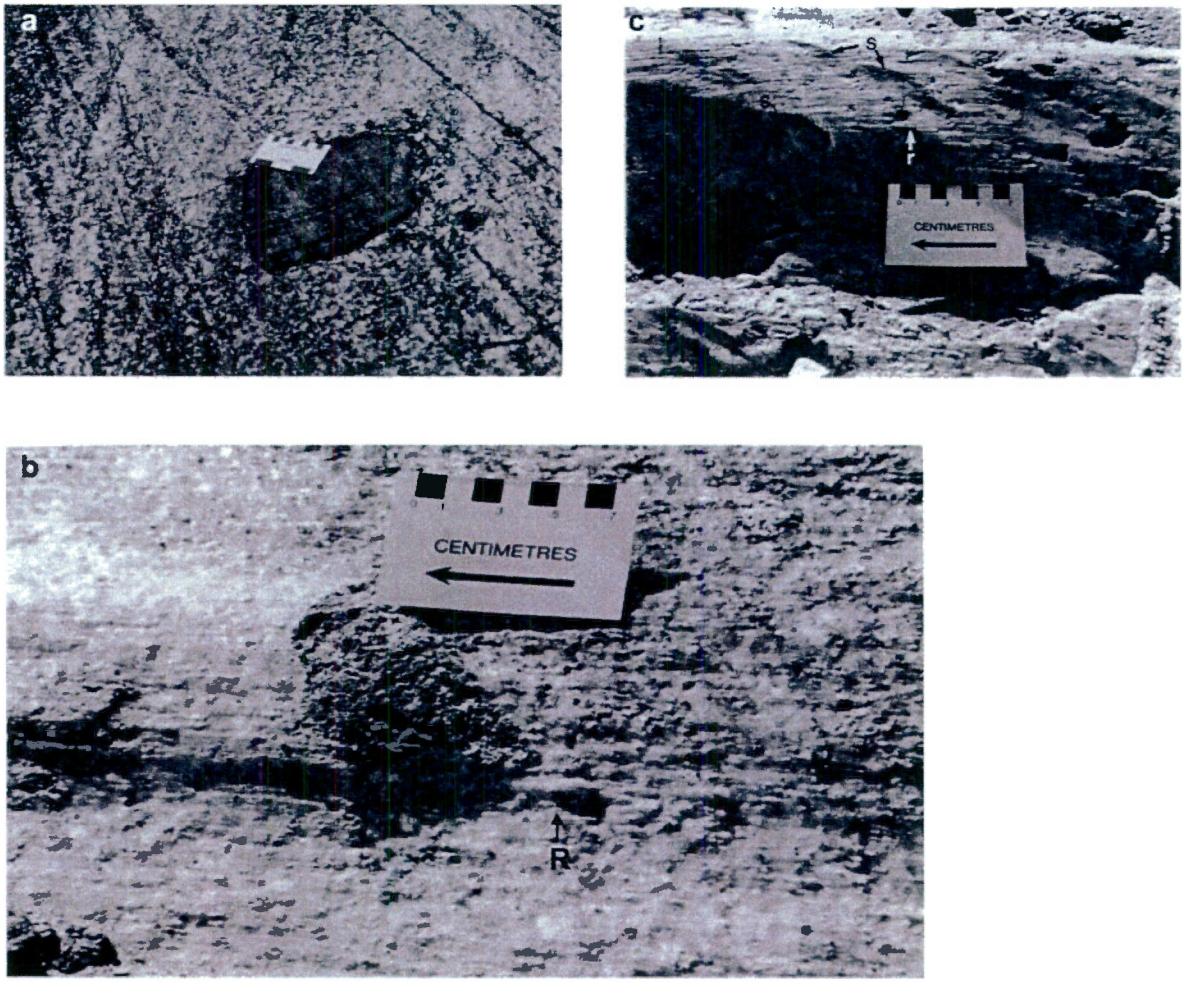
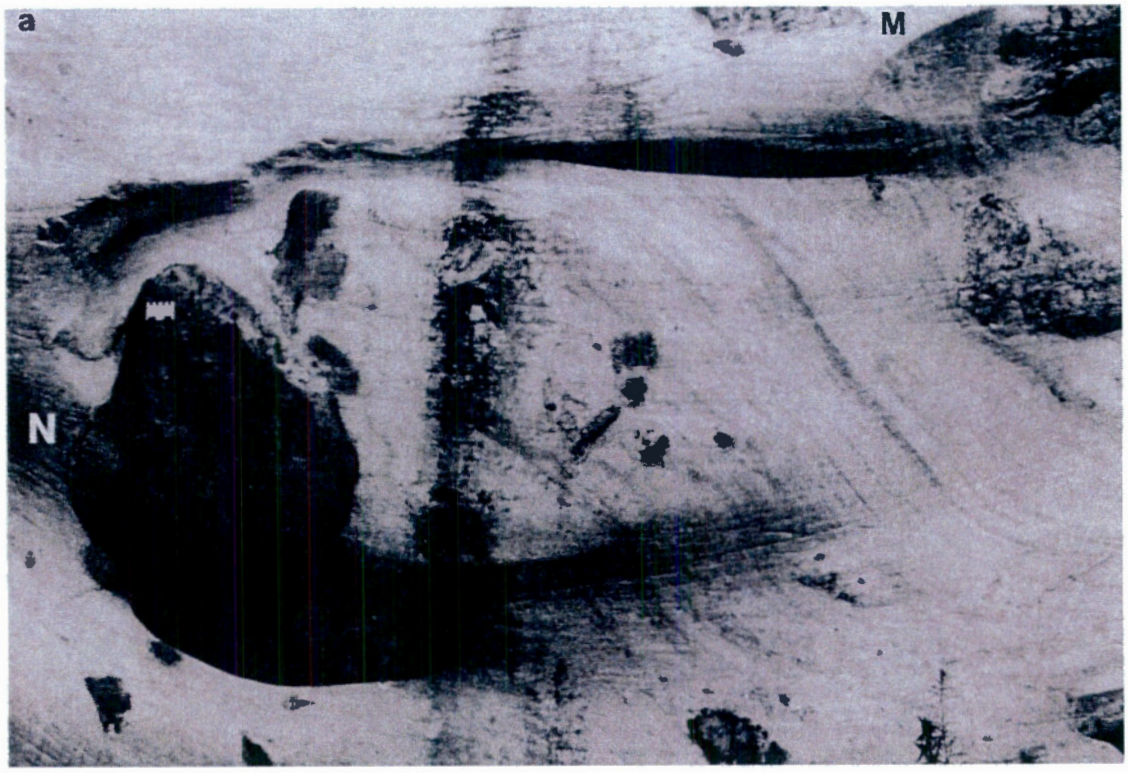


Figure 5. Small-scale forms:
a) volcanic clast in Grenville marble is planed off on a striated rock surface displaying variable striae directions; flow bottom right to top left parallel to outcrop ~N-S orientation.
b) rat-tail forms (r) (Prest, 1993), 1- 3 mm long, some with mineral grain at the head and others without. Note pitted nature on the upflow (right side) of the dark rock inclusion. Flow right to left parallel to outcrop orientation. c) rat tails set within small shallow sculpted forms (s) oriented oblique to rat tails (r). Note: scale card is 8 cm long.

Obstacle marks and sichelwannen

The most common and distinctive erosion forms at the site are obstacle marks (Fig. 6), 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. 6b). The proximal furrow commonly has a sharp leading margin. The arms of the crescentic furrow extend leeward in a pair of furrows that become shallower and wider downflow (Fig. 6a and b). The furrows are often smooth or less striated than adjacent surfaces outside the furrow (Fig 6a), and they can contain divergent flow features (Fig. 6b). Furrows also extend far downflow (Fig. 6c) 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 figures 6a, c and 4). An element (d), divergent from main flow, indicates vortex flow in the upflow furrow (F; Fig. 6c).



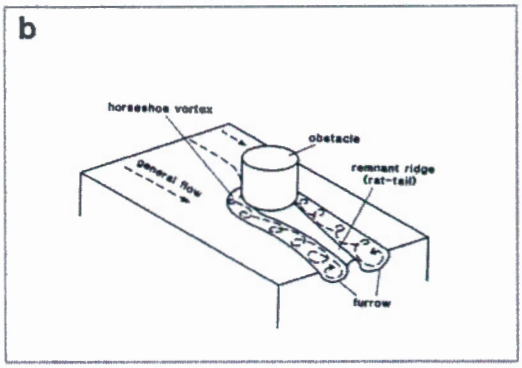


Figure 6. Obstacle marks (transverse s-forms):

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 person for scale, lower left. These forms are now described as transverse s-forms (Kor et al., 1991).

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. 4). At this scale, the remnant medial ridges can be considered to be rock drumlins (Fig. 4). A smaller, mussel-shaped transverse form (muschelbruch) occurs with sharp margins but without a medial ridge (see M, Fig. 6a).

Channels or Cavettos and Potholes

Furrows that extend down flow (Fig. 6c) 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. 7). Cavettos are commonly meters long and centimeters to meters deep, and they may crosscut other features (Fig. 7b). They may have vertical segments similar to truncated potholes (Gjessing, 1967). Vertical segments (Fig. 7c) 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.

Other features

Interior surfaces of many s-forms are scored by light scratches (Fig. 8a). 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. 8a). 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. 8a).

Pitting can occur on the upflow side of obstacles with remnant ridges (Figs. 8b and 5b). This appears to be incipient development of upflow furrows, perhaps as an emerging rock ridge is exposed to accelerated erosion (Fig. 9).

Cross-cutting forms

There are many cross-cut relationships involving striation and sculpted forms on Cantley outcrops (Fig. 6c, 7b, 7c, 8b, c and 8d). For example, striations occur as ornamentations, set at an oblique angle, on top of a transverse s-form (sichelwannen) (Fig. 8c). In some forms, rat-tails readily show divergent flow within s-forms (Fig. 7c and 8d).

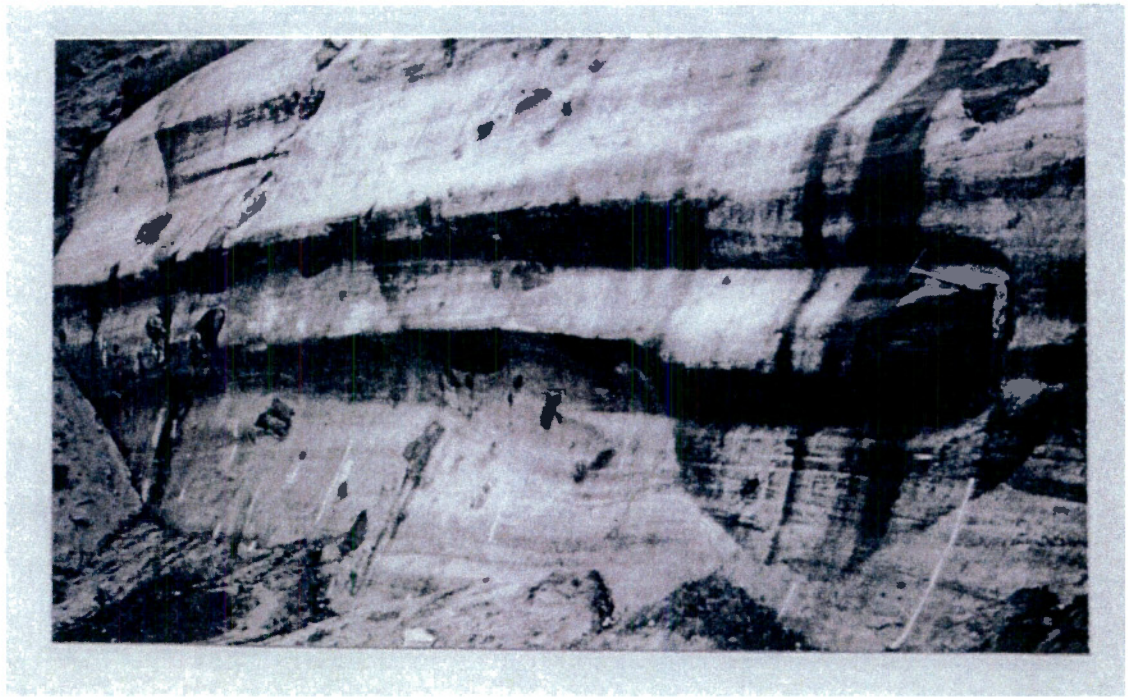
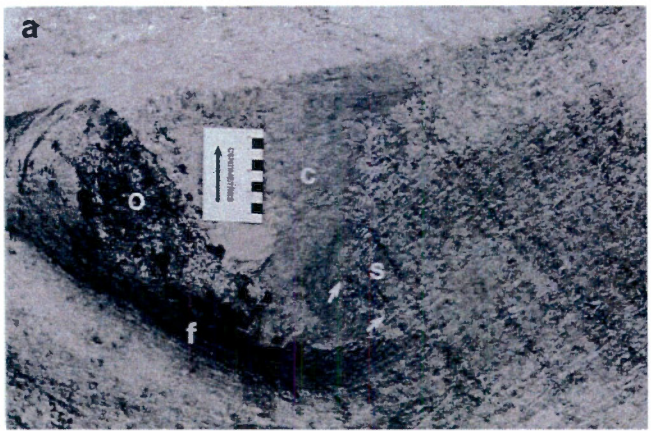


Figure 7. Furrows, cavettos and potholes:

a) Poorly-developed upflow furrow extends to lengthy longitudinal furrows (~10 m) and remnant ridge. Flow right to left parallel to outcrop orientation. Note that an artist's painting of this form appears on the fieldguide cover.

b) Complex pattern of longitudinal s-forms; furrows and cavettos. Flow left to right parallel to outcrop orientation. Note person lower right for scale.

c) 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.



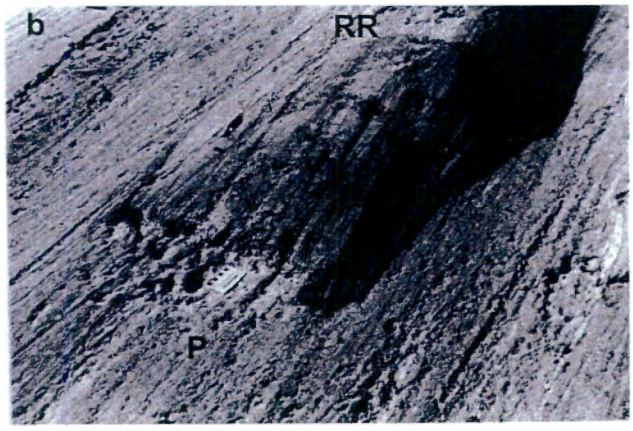
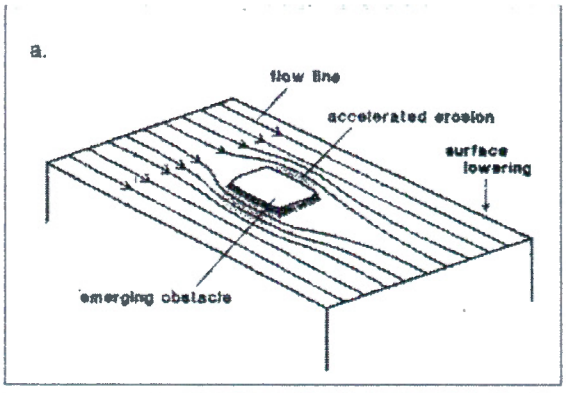


Figure 8. Other erosional features:
a) Short, light scratches occur in alignment with the axes of furrows (f) and associated remnant ridge surfaces. Carbonate precipitate (C) is also found on polished surfaces in places, particularly in the lee of obstacles (O) and on remnant ridges (see 8 cm card).
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.



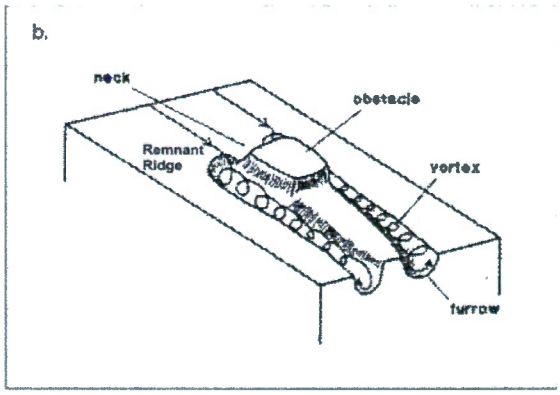


Figure 9. Schematic diagram of (incipient) obstacle mark formation under turbulent flow: a) emerging obstacle creates zone of compressed flowlines and accelerated erosion; b) paired vortices erode furrows either side of obstacle.

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 planing 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 striae, 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. 6c, 9), resulting from a vertical pressure gradient generated at the upstream face of the obstacle in turbulent flow (Shaw, 1988; 1994). This gradient sets up secondary flow and a pair of oppositely rotating vortices (Fig. 6c, 9). 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 (Fig. 9). These vortices expanded rapidly and thus, became reduced in intensity and erosional power downstream. As a consequence, the furrows would have become broader and shallower downflow (Fig. 6b, c; 9), and, rat tails, the remnant (rock) ridges between the furrows, became narrower and lower. Sichelwannen similarly relate to flow separation and horseshoe vortices (Kor et al., 1991), whereas muschelbruch 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 (Fig. 9), are preserved due to their protected location within a furrow. Most appear to represent secondary flows related to vortices within a primary flow (Fig. 9). 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, (Fig. 5b), are also identical to some sculpted fluvial forms in terrain subject to flooding in Australia (Baker and Pickup, 1986). Some larger forms (e.g. Fig. 4) are similar to forms identified within the Channelled Scablands of Washington State (Bretz, 1925; Baker, 1978). These comparisons support the interpretation of formation by water erosion. Allen (1971, 1982) also verified experimentally that erosional forms such as these, and observed on former glacier beds, 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 (Fig. 8b). Cavitation may be a precursor to horseshoe vortex erosion on the upflow side of rock rises and obstacles (Fig. 6b. 8c).

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 Hillarie-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 channelling'. Dissolution features probably relate to minor post-glacial modification of common sculpted forms that has taken place following removal of sand and gravel from the quarry rock surface in recent years.

Glaciofluvial-glaciomarine sediment

At the north end of the Cantley site, a 15 m thick sequence of glaciomarine sediments overlies the eroded rock surface. Although poorly exposed now, beds consist of a fining upwards sequence of sandy gravel and bedded sand overlain by silt and laminated clay. Marine fossils such as *Portlandia arctica, Macoma balthica, and Mytilus Edulis* may be found at the site. A similar site just to the south of the Cantley quarry also reveals glaciofluvial sand and gravel and glaciomarine mud over sculpted bedrock (Fig. 10). These sediments were deposited into the Champlain Sea as subaqueous fans at an elevation of about 170 m a.s.l; local marine limit is about 200 m a.s.l. This description contrasts with a photograph caption suggesting that 'moraine' deposits were in evidence at Cantley (Hillaire-Marcel, 2005).

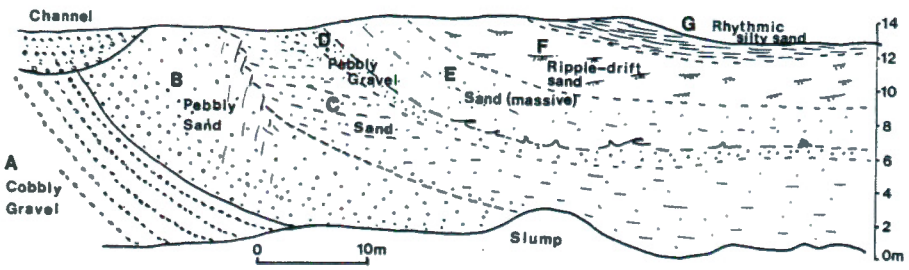


Figure 10. Field sketch of glaciofluvial and glaicomarine sediments (Sharpe, 1987), resting on sculpted bedrock (not shown) south stop site; A-G are major lithofacies.

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 (Fig. 9a, b). 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).

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., 2006), up-ice from the Cantley site. Separation of the glacier from its bed by a subglacial meltwater sheet, as in some Icelandic floods (Johannesson, 2002), 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 corresponds 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).

Regional landform patterns

The observations at Cantley raise a number of questions that can be considered during the field trip (Table 1). The most general question; can erosion features at Cantley be linked to features downflow? Southward flow-path indicators, as provided by streamlined landforms at the Cantley quarry and north along the Gatineau valley (Fig. 11), are in alignment with drumlin fields south of Ottawa (e.g. drumlin field north of Kemptville, D, Fig. 2), and identified at stop 3. The drumlin fields of eastern Ontario are probably part of a broader regional flow pattern that sweeps into the Lake Ontario basin from the northeast (Barnett et al., 1991). Regional occurrence of s-forms, striae and streamlined landforms appear to be part of this broad regional pattern (Fig. 12). A regional convergent pattern has been inferred to represent ice streaming into the Lake Ontario basin from the east-northeast (Ross and Parent, 2006), or meltwater floods (Shaw and Gilbert, 1991; Sharpe et al., 2004). Additional meltwater erosion features that are likely part of this regional pattern have been identified northeast of Kingston (Bernard, 1971; Gilbert, 1990; 2000; 2007; Gilbert and Shaw, 1994; Henderson, 1988; Murray, 1988; Pair, 1997). The regional pattern appears to be overprinted with N-S landforms, an inferred later flow pattern, evident in the Cornwall area (Terasmae, 1965; Gadd, 1980).

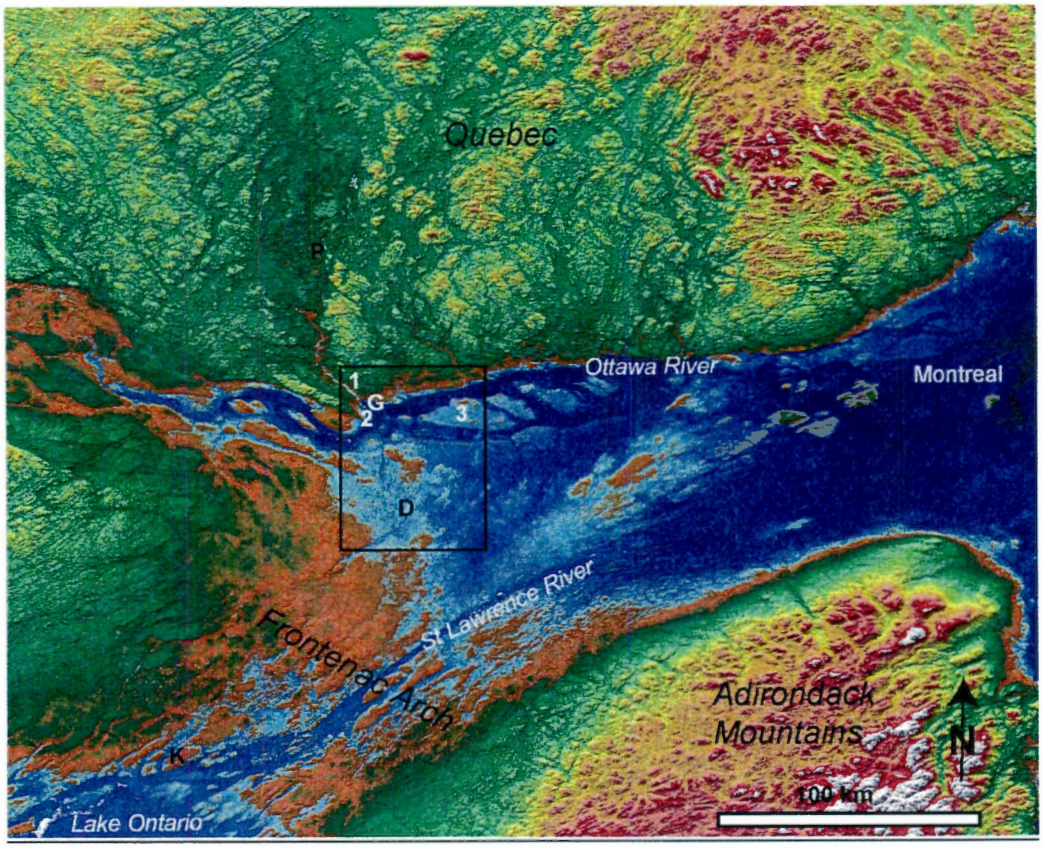
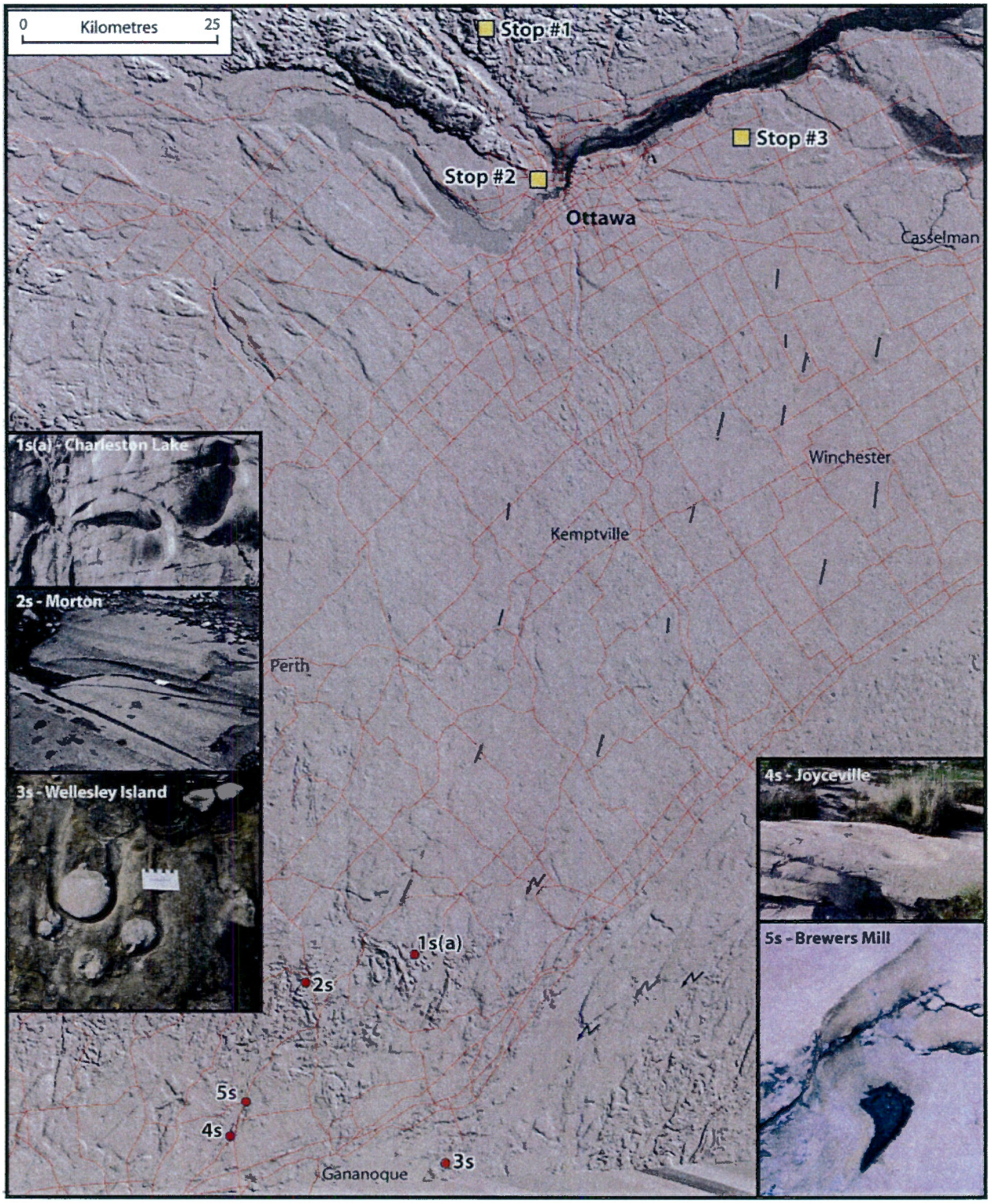


Figure 11. Regional digital terrain model of the Ottawa- St. Lawrence valley region. Note a large N-S drainage path (P), north of Stop 1, in the Gatineau valley (G).

Table 1 Key questions to pose during the field trip

1. Are sculpted erosion forms (s-forms) distinguishable from ice flow indicators (striae 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 (striae)?
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 mapping landscape?
9. Could ice streams and meltwater floods occur in closely-timed or the same event sequence?
10. Are the drumlins south of the fieldtrip area erosional or depositional? How can we test/ constrain either case?
11. If drumlins south of the fieldtrip area are erosional, how are striations under a sediment drumlin linked to the landform sediment and its orientation?



12. Regional elevation model with selected flow features (streamlined forms; short black lines and s-forms; z symbol) south of Ottawa to Gananoque. Photo portrait of some s-forms, analogous to forms at Stop 1, occur near the Frontenac axis (see figure 11).

Stop 2. Pothole in the Ottawa River valley

Directions: *Return south on 307, then west to end of Highway 50; right on rue Moncalm, 200 m; right on rue St-Laurent, 200 m.*

An exposed rock surface in Gatineau Quebec reveals an isolated ~8 m deep depression eroded into the Paleozoic carbonate rock surface (Fig. 13), situated ~10 m above the Ottawa River level. The depression has an asymmetric, balloon-like geometry with smooth, iron-stained walls. The surface opening is less than the maximum diameter of the form. The erosion form is now devoid of sediment, but it was filled with sand and gravel; coarser sediment (gravel up to 20-30 cm) appeared towards the top of the fill (Fig. 13). There are no similar features exposed in ~500 m of excavation along this section of highway and the original surface cover of the bedrock is unknown.

Figure 13. Photograph of pothole and sand and gravel fill, Stop 2, Gatineau, Quebec.

The feature is interpreted as a pothole with a high-energy fill, based on landform position downflow of Gatineau valley and within the paleo-channel of the Ottawa River (Fig. 2). Fluvial polishing appears to be present on vertical walls. Fluvial erosion (corrasion) most reasonably explains the form; flow structures on the scale of this feature were needed to yield this depth of erosion. The erosion feature could represent paleo-fluvial scouring by vortices impinging on the river bed and captured while migrating downstream during high-stage flow events or floods (Richardson and Carling, 2005). It is also possible that the feature could represent glaciofluvial erosion during subglacial or proglacial floods or high-discharge events (Allen, 1982). Karst erosion is always possible in carbonate rocks; however, the lack of other solution weathering features along the rock face makes this possibility very unlikely as the prime process explanation.

Stop 3. Terrain features on the north Champlain Sea Plain east of Ottawa

Directions: *Travel east on Highway 417 past Orleans to Trim Road; south on Trim Road to Old Montreal Road; east on Old Montreal Road to Frank Kenny Road; south on Frank Kenny Road to Wilhaven Drive. Proceed east to O'Toole Road then south on O'Toole road to stop 3 (Fig. 2).*

Purpose of the stop

This stop illustrates several elements of an erosion surface, including surface and subsurface expressions of a boulder lag on Paleozoic limestone and on thin till. Subsurface features are illustrated using innovative seismic reflection techniques: shear-wave technology helped identify boulder lags buried under Champlain Sea sediments. Other features such as eskers, a tunnel-valley and drumlins are either observed in outcrop or imaged using seismic reflections (Fig. 14). The relationship between these features and a regional unconformity is examined.

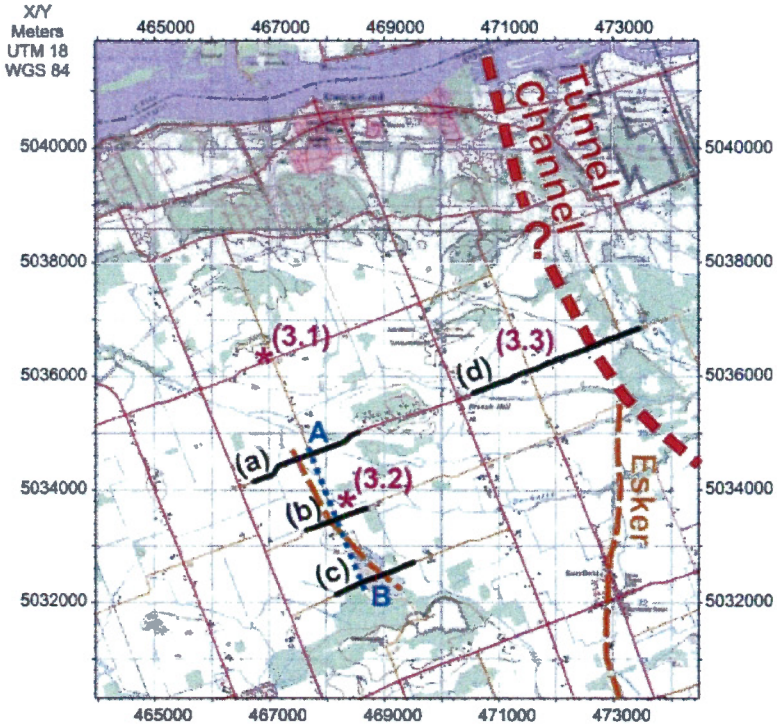


Figure 14. Map of site features, seismic lines and profiles for stop 3. Sarsfield esker is shown connecting to the inferred trend of a tunnel channel.

Stop 3.1

Boulders are numerous on a pasture forming the southern flank of a bedrock upland (Fig. 15). The boulders rest on thin (~1-3m) till forming the gentle south slope leading to the bedrock upland (Fig. 16). Most boulders are limestone with diameters up to 1m or more (Fig. 15). There are some crystalline Shield boulders (<5%) originating north of the Ottawa River. Some are angular and ~4 meters in diameter, while others are rounded and up to 2 m in diameter. Surfaces of carbonate boulders are partly weathered by dissolution.

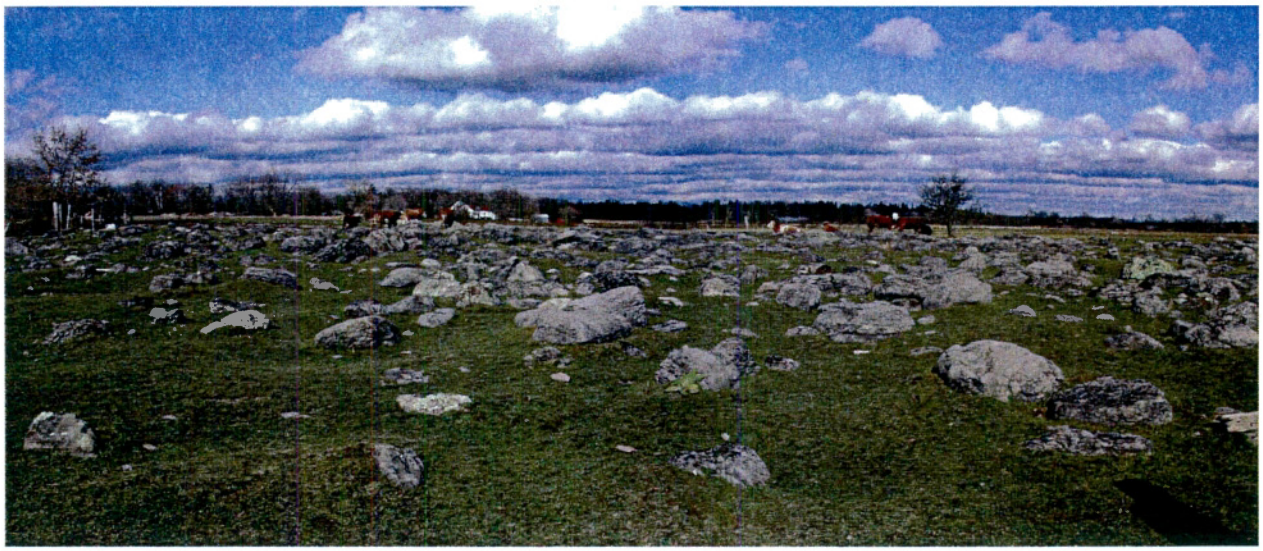


Figure 15. Photograph of exposed till surface with boulder lag (~1-1.5 m in diameter) at site 3.1.

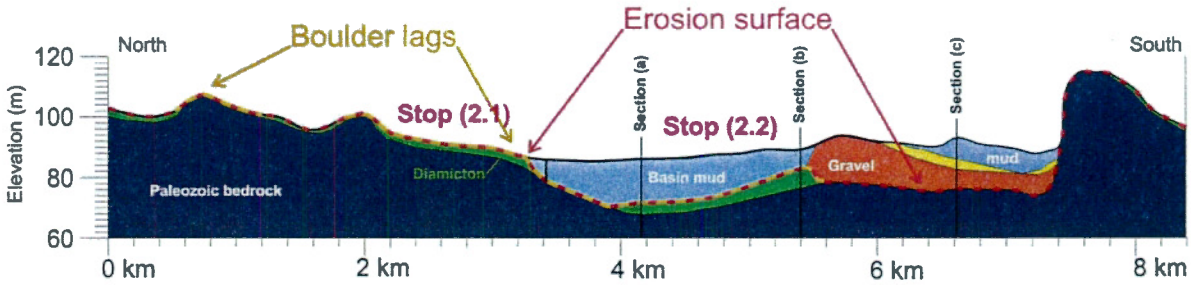


Figure 16. Cross-section of north Champlain Sea plain showing context of sites 3.1 and 3.2, boulder lag and subsurface sediments on thin till and bedrock uplands.

Interpretation:
The boulders form a lag from eroded till that may be attributed to one, or combined effects, of: i) littoral washing by the Champlain Sea, ii) scour by an ancestral, high-level, Ottawa river, iii) scour during glaciofluvial events. Nearby littoral features occur at ~110 m asl; high-level sediment terraces occur at m ~85m asl; north-facing rock scarps occur at 118 m asl; and, glaciofluvial erosion may have occurred between ~70-120 m asl (Fig. 16).

Stop 3.2 Seismic reflection profiles
Section (a), (Figure 14) French Hill Rd. West
This 2 km long shear-wave seismic section displays diverse features (Fig. 17) that can be linked to surface forms and drill-core results. The east-west section was acquired on flat terrain with little geomorphic expression (Fig. 14). Water well records indicate ~5-15 m of surface mud (Fig. 16). An upper, low-reflectivity package can be subdivided into two units (Fig. 17), separated by a strong reflection generated by two different velocity/density elements (Table 2). The lower "Basin mud I" has an average interval velocity of ~160 m/s. The upper "Basin mud II" is a more

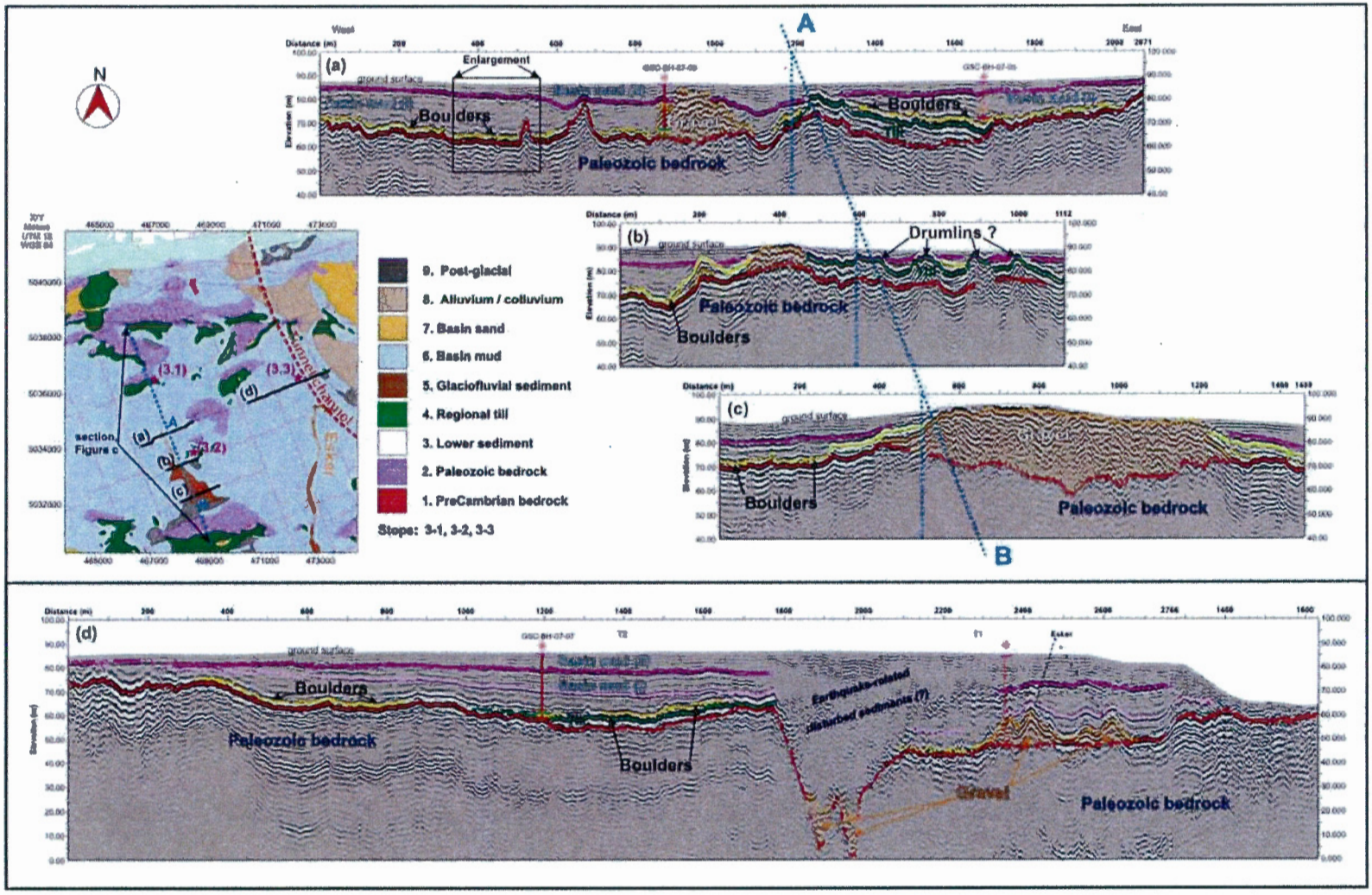


Figure 17. Stop 3 seismic profiles: a) ~2 km long profile displays eroded bedrock and till surfaces with sand and gravel lag, and esker sand and gravel below two basin mud units; note GSC boreholes. Square show figure 18 location with inferred rock drumlin; b) ~1 km profile displays scoured rock surface and sediment drumlins with overlying sand and gravel as inferred lag; c), ~1.5 km long profile: eroded rock surface overlain by sand and gravel lag and esker sediment; d) ~1.6 km profile: eroded bedrock till surface with overlying glaciofluvial sediments in channel and eskers. GSC boreholes provide groundtruth data.

transparent and reflective unit, and has an average interval velocity of 125 m/s. Basin mud stratigraphic units, regional correlation and borehole logging results are reported in detail by Cummings and Russell (2007).

Basin muds bury an irregular topography. Strong reflections at the base of the mud can be subdivided into three seismic facies, **x, y** and **z** (Table 2). Facies **x**, observed on section a (0-850 m; and 1700 m to end of section) has a double phase reflection pattern. The first phase is light, but it has lateral variations in amplitude; the second phase is strong and continuous (Fig. 17).

Figure 18 shows a detailed part of this section (Fig. 17). The upper panel displays the seismic section in amplitudes (Fig. 18a). Amplitudes display a smoother diffractive phase that does not distinctly displays lateral lithologies or small objects (e.g. boulders). Migration collapses diffractions into single points of energy and a granular structure can be seen (Fig. 18b). By displaying the absolute energy of the amplitude (i.e. envelope), the "migrated-envelope" section highlights the top of the bedrock reflection as a granular surface (Fig. 18c). The granular surface is interpreted as a boulder lag resting on limestone bedrock.

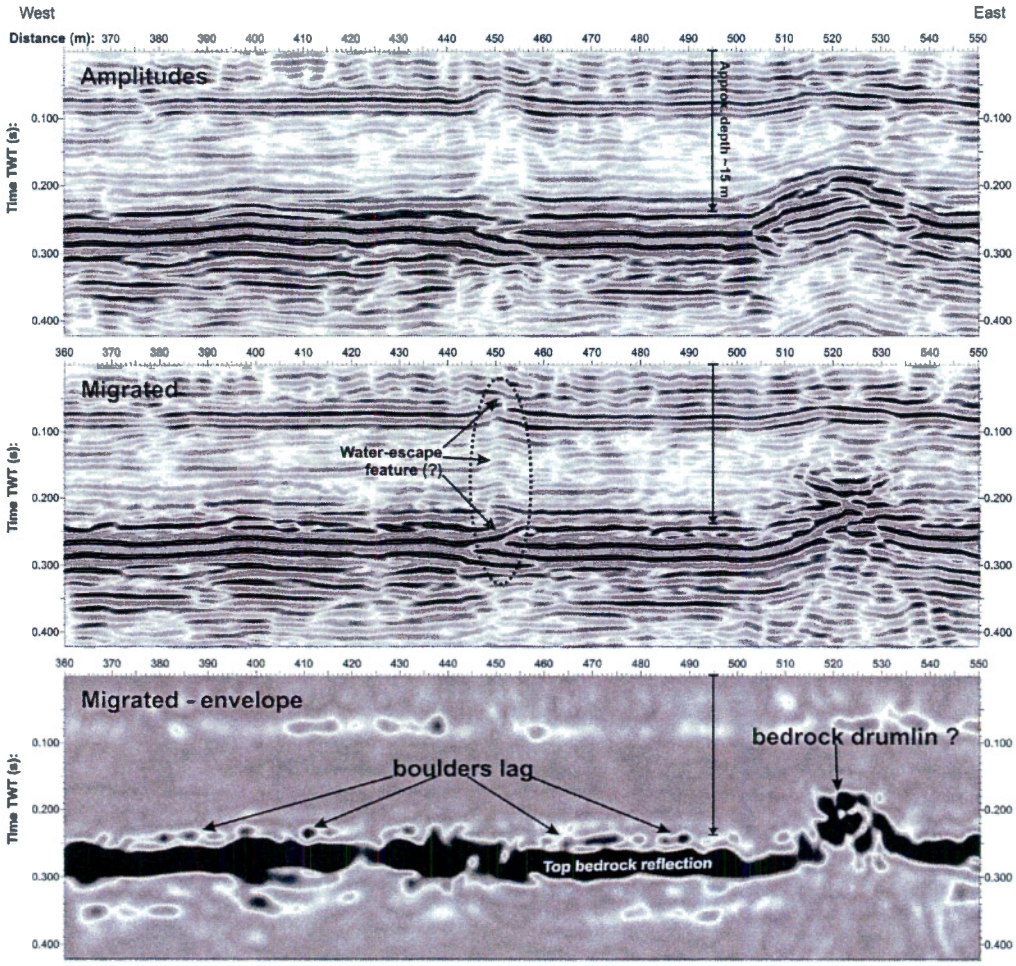


Figure 18. Seismic profile a) 300-500 m west: amplitude, migrated and envelope. Interpreted reflectors display eroded bedrock surface, inferred rock drumlin and boulder lag on this surface.

A highly diffractive feature can be seen between coordinates 500-540 m (Fig. 18). Here, the 'migrated envelope' section has the form of a steep edge with a flat top (Fig. 18c). This structure may be interpreted as a bedrock drumlin similar to the sculpted rock drumlins seen at Cantley (stop 1). A similar buried hill can be observed in section (a) (Fig. 14), at the coordinate 670 m with the top of the hill almost reaching the ground surface. This hill is about 12 m high and has a basal width of ~40 m (Fig. 14). At coordinate 450 m (Fig. 18), a vertical structure above a disturbed bedrock reflector could be interpreted in several ways: 1) as a possible vertical water-escape feature situated above bedrock (karst?); groundwater flow in this area is artesian; or, 2) the disturbed zone is related to recent tectonic ground movements.

The second facies **y** present at the base of the Basin Mud, coordinates 840-1100 m (Fig. 17), is characterized by discontinuous, medium-high amplitudes that overlie semi-continuous curved reflection patterns. Based on outcrop and facies calibration in the Sarsfield-Winchester esker, this dome-shaped structure is interpreted to be a coarse gravel ridge. A weak reflector at the base of the reflection pattern is interpreted as the top of limestone bedrock. Drilling results from April 2007 confirm the presence of a coarse gravel ridge (esker) resting on bedrock (Fig. 17). See also Cummings and Russell (2007).

The third facies **z** has similar characteristics to the first facies (Table 2): strong reflectors are covered by a granular structure. The strong reflection is followed by a strong pattern of continuous phases. A second weak reflector can, in places, be observed below the main reflection. Based on sediments in outcrop and borehole core, to the north and the south of the section, the third facies is interpreted as a diamicton, and till in this setting. Boulders can be observe at the top of this facies (Fig. 17 a).

Section (b), (Fig. 16) Regimbald Rd.
All seismic facies described in the previous section (a) are present at section (b). Basin mud (20 m) lies directly on bedrock (facies **x**) with overlying boulders on the west end of the section. The second facies, y, outcrops on the side of the road as coarse gravel. A sequence of four domes, under the basin mud, is observed on the eastern side of the section (Fig. 17 b). The height of the hills is ~10 m. Borehole data confirms ~1-2 m of diamicton on this eastern side of the line (Fig. 17). The eastern hill correlates with a till drumlin situated just north of this section (Fig. 19).

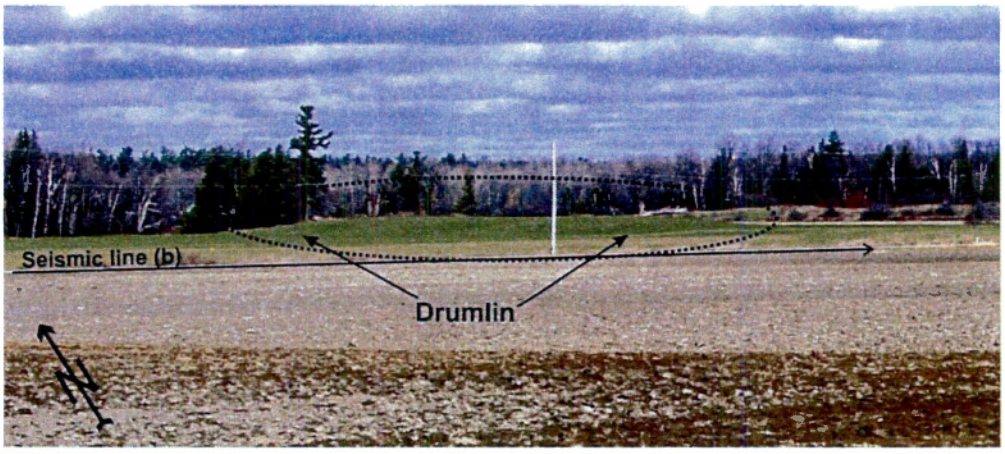
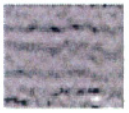


Figure 19. Drumlin oriented SSE at site 3.2; NS-oriented drumlins occur south of this site.

Section (c), (Fig. 16) Giroux Rd.
The third section occurs across a large gravel ridge (Richard et al., 1974; Gorrell, 1991; Fig. 17 c). Dome-shaped relief occurs along the road which runs adjacent to a large gravel excavation that revealed glaciofluvial sediment (Gorrell, 1991). Here, seismic facies define a dome with curved and trough-shaped reflectors (Fig. 17c). These suggest the presence of internal erosion surfaces and cross-bedded stratification. On both sides of the dome, medium-amplitude reflections indicate the presence of sand. To the west of the dome, a boulder lag is also present as a major diffraction, including a large boulder (~4 m), at coordinate 130 m. This boulder compares in size with the large boulders observed at stop 3.1.

Table 2 Seismic Facies in Champlain Sea Basin

w2	medium continuous amplitudes (basin mud II) -shear velocity estimate is ~125m/s	
w1	small continuous amplitudes (basin mud I) -shear velocity estimate is ~160m/s	
x	strong, double phase reflection pattern (top bedrock covered with boulders)	
y	discontinuous, undulating, medium-high amplitudes (coarse gravel)	
z	strong continuous reflector with an upper granular structure (till covered with boulders)	

Stop 3.3
Section (d), (Fig. 17) French Hill Road East
This section traces the northern extent of the Sarsfield esker beneath the level Champlain Sea clay plain (Fig. 14). The west half of the section (to coordinate 1800 m) has similar facies to those in previous seismic lines (Fig. 17 a, b, c). A boulder lag with sand is inferred to be present above limestone bedrock or above a thin, 1-2 m, till layer. Drilling results confirmed a thin layer of sand, gravel, and boulders resting on eroded till and bedrock (Cummings and Russell, 2007).

An unexpected deep trough, coordinates 1800-2000 m, was imaged on this line (Fig. 17). The trough is filled with 80 m of sediment displaying a chaotic diffraction seismic facies. The

shallower part is less chaotic with discontinuous reflections forming a large trough. The chaotic facies may be related to piping, to sedimentary disturbance related to rapid sedimentation or to shaking from earthquake events known to occur in the Ottawa area. High amplitude, undulating facies at the base of the trough are inferred to be sand and gravel.

Seismic facies analysis indicates that undulating topography east of the deep trough may include erosion features on bedrock or on till and deposition of gravel and sand (Fig. 17, d). The western ridge appears to be of gravel, based on hummocky reflectors, and was confirmed with recent drilling results (Cummings and Russell, 2007). Other ridges to the east may also contain gravel, although they display typical discontinuous higher-amplitude facies indicative of bedrock or thin till on bedrock.

Summary

Stop 3 seismic data and borehole results include:

1. A thin discontinuous till and adjacent bedrock surfaces carry a lag of boulders that defines an erosion surface.
2. The bedrock surface has ridges that are inferred in places to be rock drumlins; in other areas ridges may be sediment drumlins.
3. The erosion surface includes a bedrock valley that may have pre-existed formation of the regional unconformity, but was re-occupied and perhaps enlarged as part of a widespread erosional event; a coarse sand and gravel unit overlies the erosion surface at the valley floor.
4. There is evidence in seismic facies and drill core results that indicate a discontinuous layer of sand and gravel on the erosion surface. These form important local aquifers.
5. In several places, the sand and gravel layer is thick and appears to form esker ridges and a coarse fill at the base of a buried valley. These form important high-yield aquifers.
6. The erosional lag on rock and till surfaces below the Champlain Sea clay can be linked to the same features observed in outcrop at stop 3.1 (e.g. Fig. 15)
7. The occurrence of the erosion surface and lags above and below the Champlain Sea sediments, rules out littoral and proto-Ottawa River processes, and supports the inference of regional glaciofluvial processes to explain the stratigraphic context.
8. Stop 1, Cantley quarry, provides evidence of glaciofluvial erosion and rock drumlins overlain by glaciofluvial sediments and marine clay.
9. Similar features occur within the Champlain Sea basin east of Ottawa, and they provide further support for a regional unconformity. Figure 20 provides a conceptual sketch what the stratigraphic context of the late-glacial unconformity in the Ottawa region.

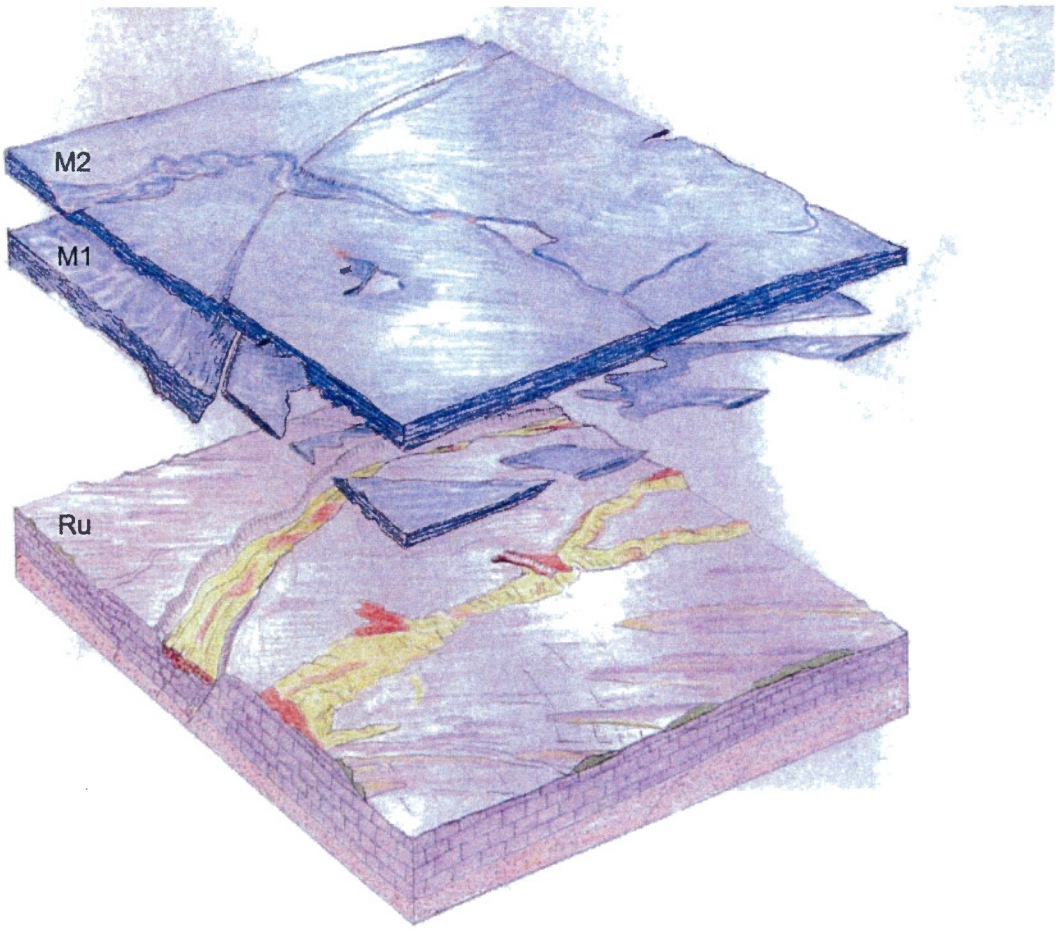


Figure 20. Schematic block diagram of the Ottawa region (view SE): displays elements of the proposed regional unconformity on the bottom layer (RU), with overlying channel and esker glaciofluvial sediment. Two basin mud layers (M1, M2) overlie the unconformity and coarse sediment layer. Drawing; John Glew, Queen's University.

Discussion

Rapid flow events

Streamlined features such as the rock drumlins and other erosional forms at Cantley are interpreted as evidence of rapid glacier flow (e.g. Dowdeswell and Elverhøi, 2002). Rapid glacier flow is equated with ice-streams within ice sheets (Alley et al., 1986). In some cases, enhanced flow rates affect portions of the glacier in topographically constrained valleys (e.g. Bennett, 2003), perhaps similar to Gatineau valley or its tributaries. It is also inferred that fast flow in ice streams is caused by a deforming till bed (O'Cofaigh, et al., 2005) or, enhanced sliding under high basal water pressures (Englehardt and Kamb, 1998; Thorsteinsson and Raymond, 2000). Modern ice-stream studies indicate a link between ice-stream location and a soft sedimentary substrate. Soft substrates may explain the location of paleo-ice streams. Yet, such a relationship is not universal as paleo-ice streams have been inferred in areas of hard, or crystalline, bedrock (Roberts and Long, 2005) (perhaps Cantley, Stop 1). On the other hand, Alley et al., (2000) suggested that it is unlikely for subglacial deformation to have operated on a

hard-rock substrate. If rapid glacier flow is to occur on such a substrate, it would have to be a result of high water pressure (e.g. figure 7c). Several recent studies highlight the increasing role of subglacial water to rapid flow events (Siegert and Bamber, 2000; Siegert et al., 2005; in press).

The distribution of diamicton in the area is an issue related to rapid flow and erosion. Deforming till beds are not only linked to rapid flow, they are inferred to be agents of erosion in streamlined bedrock (e.g. O'Cofaigh et al., 2005). There is a lack of diamicton in the Cantley quarry above the bedrock erosion forms (Stop 1) and it is scarce along the Gatineau River valley (Richard et al. 1974). As well, there are no reports of 'till deltas' (e.g. Anandakrishnan et al., 2007) in the adjacent Champlain Sea basin where till is thickest in sediment drumlins (Fig. 20). Elsewhere, results from Stop 3 indicate thin discontinuous till with a boulder lag, set below the proposed regional unconformity. Thus, it is highly unlikely that sculpted bedrock forms in the Gatineau valley were eroded by deforming till beds.

Subglacial lakes

Recent evidence from Antarctica indicates that large subglacial lakes initiate and maintain rapid ice flow (ice streaming) through lake accretion (Alley et al., 2006) or, periodic drainage events (Bell et al., 2007). Movement of subglacial water between subglacial lakes and along ice streams was documented by recording rapid surface elevation change (Wingham et al., 2006; Fricker et al., 2007). This recorded cycle of drainage and filling may have a significant influence on ice stream velocity, on time scales of weeks to months (Siegert et al., 2005). The Antarctic data supports the role of subglacial lakes in ice-sheet drainage events predicted from theory (Shoemaker, 1992; 1999). A subglacial flood can take the form of a sheet (Flowers et al., 2004) rather than the well-studied and generally accepted tunnel form (Nye, 1976; Clarke et al., 2005), and this causes rapid ice flow and advance. Shoemaker (1994) also showed that flow turbulence greatly increases the characteristic time for an "unstable", meters-thick water sheet to be viable: it can exist on the order of a month. He also inferred correctly that erosional drumlins should tend to exist in those regions where water-sheet velocities are high (uplands), and they should be absent in regions where velocities are very low (low ground). Thus, ice streaming may be associated with the storage and release of subglacial meltwater (Siegert et al., in press) that could account for unconformities and a variety of subglacial landforms.

Landscape unconformities- regional erosion surfaces

Seismic stratigraphy, geometry and seismic/sediment facies record well-defined erosional surfaces, mainly mapped in offshore Quaternary terrains (e.g. subsurface tracts with overlying incised channels, Posamentier and Allen, 1999). Mapping regional erosion on late-glacial landscapes has been related primarily to base-level control, and recently, to Pleistocene floods (Fulthorpe and Austin, 2004; Uchupi, et al., 2001).

Landforms and associated flow patterns are also used to re-construct regional erosion surfaces, unconformities, on land (e.g. Shaw, 1996; Kor et al., 1991; Gilbert, 1994; Munro-Stasiuk et al., 2005). Landform mapping and sedimentology have been used to infer either ice (e.g. Boyce and Eyles, 2000) or meltwater (e.g. Shaw and Gilbert, 1990) as the primary agent of erosion. Mapped landform relationships and analysis of event-sequences permit an ongoing field test of unconformities and inferred regional meltwater processes across the eastern Great Lakes region (e.g. Sharpe et al., 2004; Gilbert, 2007). For example, a late-glacial unconformity is identified

based on scoured bedrock tracts, upland drumlin fields, channel networks, boulder lags and coarse channel fills, using seismic profiles linked to cored boreholes and terrain mapping (Sharpe et al. 2004). Similar evidence has been identified on this trip (Fig. 20). This evidence constrains inferences on landscape-forming processes: i) ice surging (Kamb et al 1985), ii) deforming beds (e.g. Boyce and Eyles, 1991), and, iii) large meltwater discharges (e.g. Mullins et al., 1996; Sharpe et al. 2004). The inter-regional extent of the late-glacial unconformity can be inferred from mapping contiguous elements (Fig. 21; e.g. local; s-forms, drumlins; to mid range, scoured bedrock, transverse features, channels; to regional, mega-lineation and flowpaths, e.g. Bernard, 1971; Gilbert, 2007; Henderson, 1988; Murray, 1988; Pair, 1997).

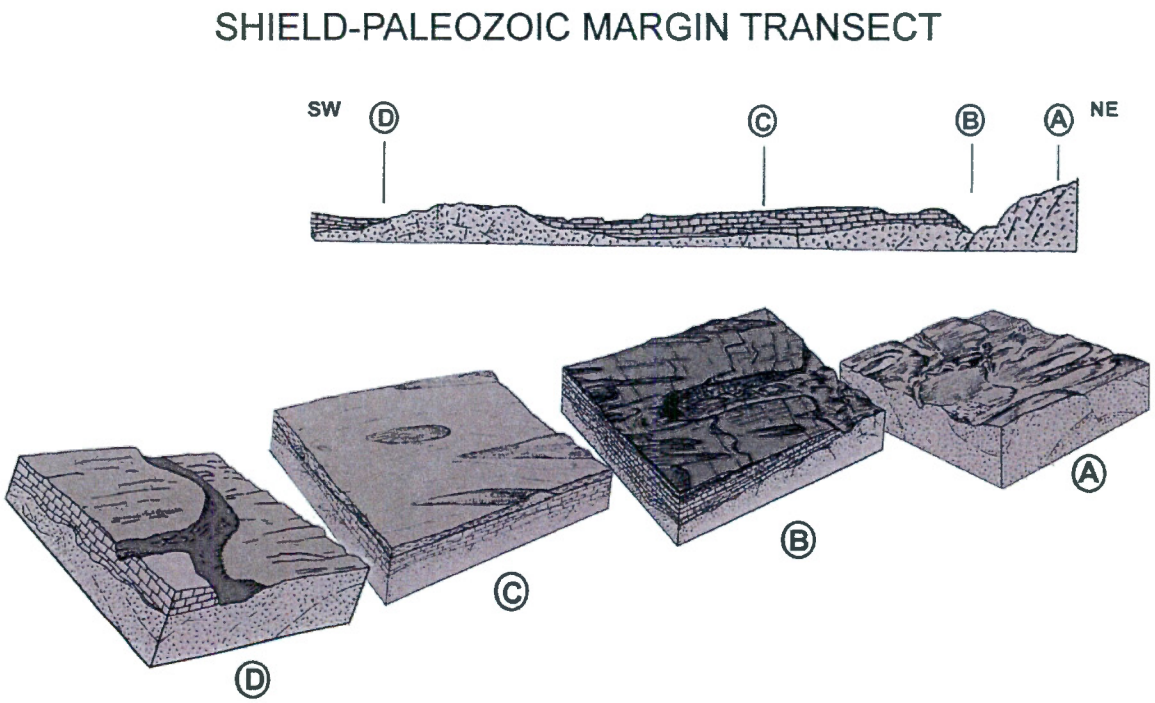


Figure 21. Landscape transect along an ~NE-SW flowpath on erosional terrain from the Gatineau Hills to the Frontenac axis north of Kingston. It is inferred to be part of a regional unconformity in eastern Ontario with the following feartures: a) s-forms, rock drumlins; b) streamlined forms, spindle rock drumlins, buried valley; c) s-forms, escarpment noses and crescentic furrows, channels on Paleozoic scarps; d) streamlined sediment drumlins cross-cut by tunnel channels.

We return to the questions within Table 1 to close out the fieldtrip. What questions/ suggestions do fieldtrip participants have, as to how to interpret and re-construct late glacial landscapes in eastern Ontario?

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Appendix I

Methodology: Shallow seismic reflection methods and borehole geophysical logging (Susan Pullan and André Pugin)

Shallow Seismic Reflection Methods

Land-based seismic methods are geophysical techniques which use measurements of the time taken for acoustic energy to travel from a source on the surface through the subsurface and back to a series of receivers on the ground. Energy is refracted or reflected at boundaries where there is a change in acoustic impedance (the product of material density and seismic velocity). Because contrasts in acoustic impedance are generally associated with lithological boundaries, seismic techniques can be used to obtain subsurface structural information. This section briefly outlines the application of shallow seismic reflection methods to delineating the structure of unconsolidated sediments and the underlying bedrock surface.

Seismic reflection methods have been the primary geophysical tool used in oil and gas exploration for over 60 years. Because of the tremendous commercial importance of oil, much industrial research and development has been invested in this branch of geophysics. By the 1960s, specialized field procedures, digital magnetic tape recording, and computer processing of the data had become standard in the industry. Conventional seismic reflection techniques are highly sophisticated, but require considerable investment in both data acquisition and processing.

In the early 1980s, the development of digital enhancement engineering seismographs with high-pass filtering capabilities and the proliferation of increasingly powerful micro-computers, began to make the application of seismic reflection methods to "shallow" problems a viable alternative. Over the last 20-25 years, much experience and expertise in the application of shallow high-resolution reflection techniques have been gained, and today these methods are accepted and proven shallow geophysical tools. Seismic reflection techniques can be applied using compressional (P-wave) or shear (S-wave) energy. Compressional waves are those in which the particle motion and direction of wave propagation are the same, whereas shear waves are those in which the particle motion is normal to the direction of wave propagation (Fig. I-1).

Seismic reflection methods involve measurement of the time taken for seismic energy to travel from the source at or near the surface, down into the ground to an acoustical discontinuity, and back up to a receiver or series of receivers on the ground surface (Fig. I-2a). Data are usually acquired continuously along a survey line, and processed to produce a seismic section which is a two-way travel time cross-section of the subsurface (Fig. I-2b). Velocity-depth functions calculated from the data, or from seismic logging of a nearby borehole(s) are used to translate the two-way travel time into depth.

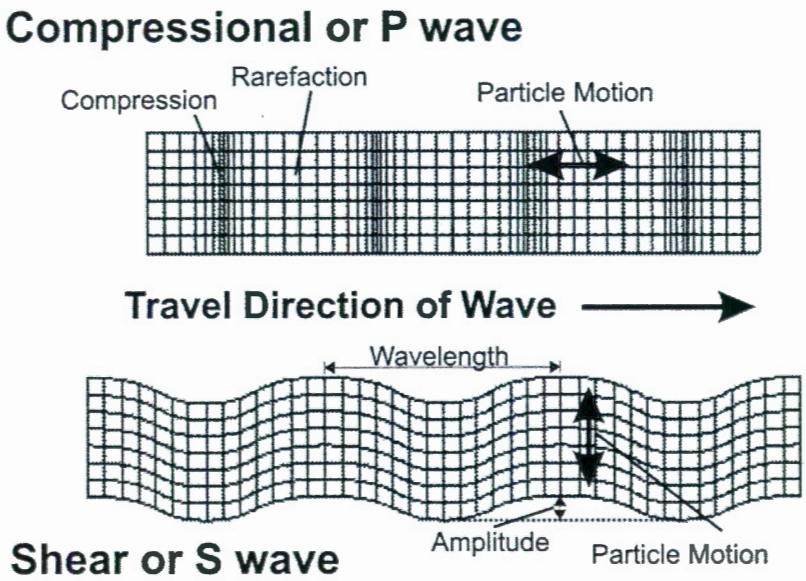

Figure I-1: Schematic diagram showing the particle motions for compressional or P waves (upper panel) and shear or S waves (lower panel).

Today, virtually all shallow seismic data are collected and processed based on the common midpoint (CMP) method (often also referred to as the common-depth-point, or CDP, method) which is an adaptation of the methods used by the petroleum industry. In CMP surveys, multi- (12, 24, or more) channel data are recorded for each shotpoint. During processing, the data are sorted according to their common midpoints or common depth points (Fig. I-3). Each trace is corrected for offset according to a velocity-depth function determined from the data (normal moveout, or NMO, corrections). A standard sequence of CMP data processing steps includes trace editing, static corrections, bandpass filtering, gain scaling, velocity analyses, normal moveout corrections and finally, stacking of the NMO-corrected traces in each CMP gather to create a single trace on the final section. This stacking procedure is the essence of the CMP technique, and allows a potential improvement in the signal-to-noise ratio of the data according to the square root of the fold (number of traces summed to produce the final processed trace at a given point along the seismic profile).

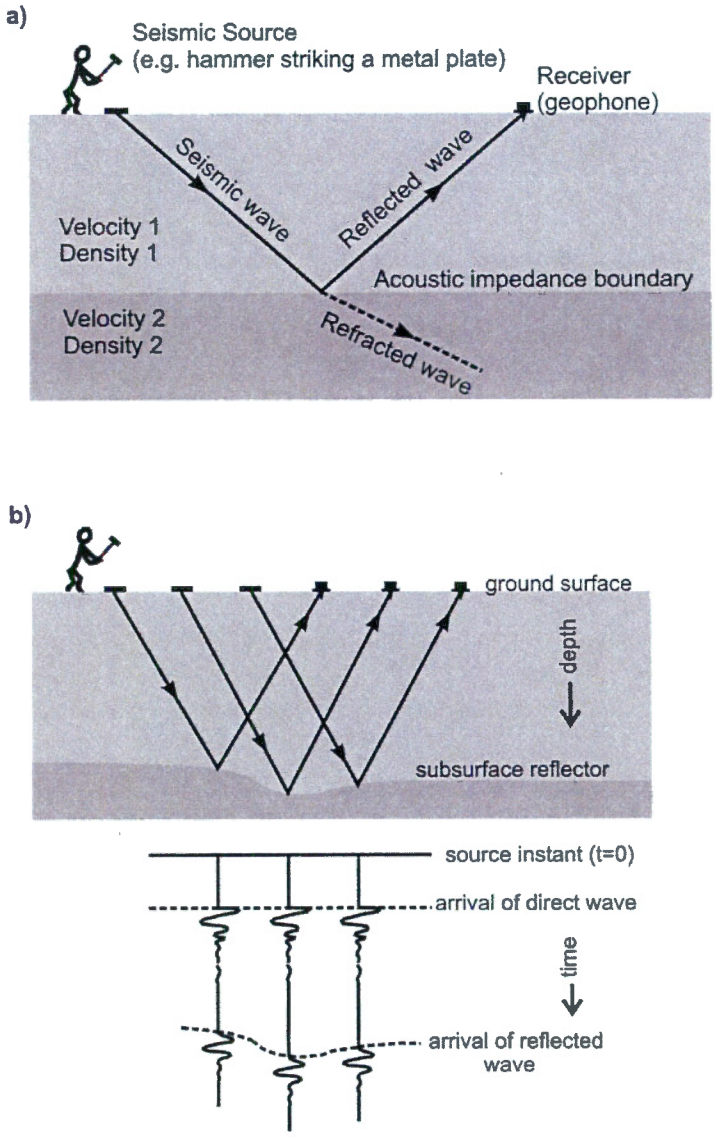

Figure I-2: Basic premise of seismic reflection methods. a) Seismic energy produced on the ground surface travels from the source down to an acoustic impedance (product of density and velocity) boundary, where it is partially transmitted and partially reflected back towards the surface. b) Data are usually acquired continuously along a survey line and the record of ground motion as a function of time is related to the subsurface structure.

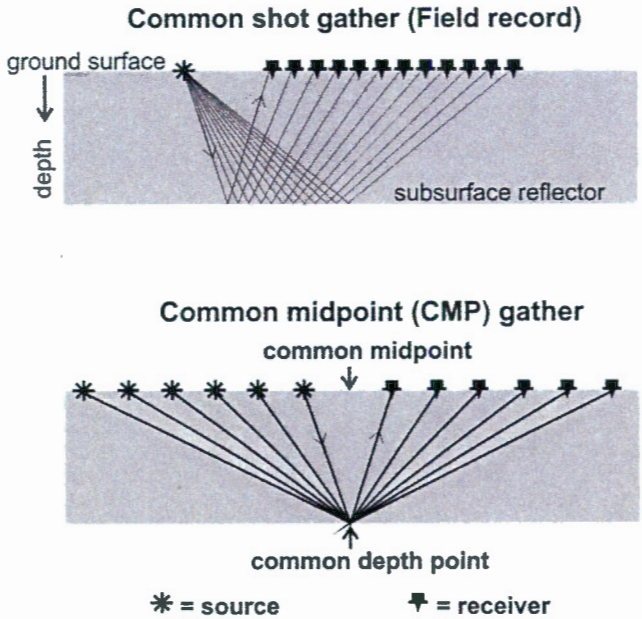

Figure I-3: Schematic diagram showing a) the subsurface travel paths of reflections from a field record and b) a common midpoint gather. The traces in the CMP gather will be processed and stacked together to form a single trace on the final CMP section (6-fold).

The successful application of any shallow reflection survey depends on the detection of high-frequency energy reflected from velocity discontinuities within the subsurface. However, earth materials, and especially unconsolidated overburden materials, are strong attenuators of high-frequency energy. Thus, compressional (P) seismic waves in the 10-90 Hz range commonly used in petroleum exploration may be reflected from depths of thousands of metres, but energy with frequencies above 100 Hz normally only have travel paths on the order of tens or hundreds of metres. The ability of a particular site to transmit high-frequency energy is a major factor in determining the quality and the ultimate resolution of a shallow reflection survey.

The optimum conditions for shallow reflection surveys (P-wave) are usually when the surface materials are fine-grained and water-saturated; reflections with dominant frequencies of 300-500 Hz can be obtained in such field situations. These frequencies correspond to seismic wavelengths in unconsolidated overburden materials on the order of 3-5 m, with a potential subsurface structural resolution of approximately 1 m. Experience has shown that excellent high-resolution, P-wave, seismic reflection data can be obtained where water-saturated, fine-grained Champlain Sea sediment is exposed at the surface (Fig. I-4).

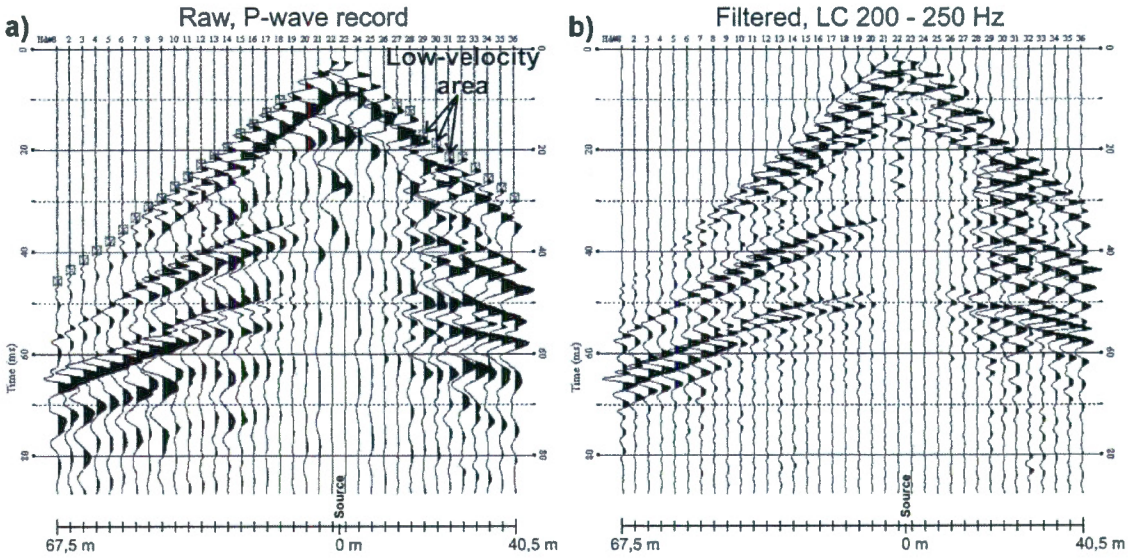

Figure I-4: Example field shot gather obtained during the P-wave reflection survey using a 12-gauge shotgun source and 50 Hz vertical geophones at 3 m spacing: a) raw record, b) same record after high-pass filtering. These records show excellent reflection energy (hyperbolic events).

Shear wave reflections are commonly much lower in frequency (10-100 Hz) than shallow P-wave reflections. However, resolution of the seismic signals depends on the signal wavelength (higher resolution associated with shorter wavelengths). As the velocity of shear waves in unconsolidated materials can be an order of magnitude lower than the P-wave velocity of the same sediments (particularly if those sediments are water-saturated), the resolution of shear wave data can exceed that obtainable with P-wave data.

Seismic profiles are sections in two-way travel time (not depth). Velocity functions are estimated from the seismic data at intervals along the line during the processing sequence, in order to calculate the normal moveout corrections applied to the data before the stacking procedure, and these velocities can also be used to convert the two-way travel time section to a depth section. However, velocities determined from reflection data can be subject to large uncertainties, depending on the moveout of reflection events. Whenever possible, accurate downhole velocity data from borehole measurements should be obtained in support of the seismic reflection survey (Hunter et al., 1998).

Further discussion on the application of seismic methods to geomorphic and environmental problems can be found in Pullan and Hunter (1999). Steeples (1998) provides an overview of the development of shallow seismic reflection techniques, and the suite of papers in that special issue of Geophysics provides a summary of the state-of-the-art of shallow seismic reflection at that time.

Seismic Landstreamer/Minivib System

Shallow seismic reflection surveys are a powerful tool for mapping detailed subsurface structure, with applications in a wide variety of groundwater, hazard, engineering and environmental investigations. More widespread use of this technique has been limited partly by the time and cost involved in acquiring and processing the data. The efficiency of data collection is largely dependent on the time required to individually plant every receiver (geophone) and to move and reconnect seismic cables as the survey proceeds along a seismic line. As well, the ability to produce and record high-frequency energy for shallow seismic reflection surveys depends on the ground conditions, the effectiveness of ground coupling for both the receivers and the source, the frequency and energy of the seismic source, and the source and receiver spacings (which define the fold – see Fig. I-3).

The Geological Survey of Canada has recently been successful in mating the IVI (Industrial Vehicles International, Inc) minibuggy minivib source (http://www.indvehicles.com) and landstreamer receiver arrays (both P-wave and horizontally-polarized shear (SH-) wave). The seismic landstreamer/minivib system is one way of addressing both the efficiency of data collection and data quality (improvement of signal-noise ratio by decreased source and receiver spacings).

Landstreamers consist of towed arrays of geophones fixed on sleds and have been demonstrated to be an efficient means of recording shear-wave reflection data (e.g. Inazaki, 2004, Pugin et al., 2004). The Geological Survey of Canada has built an SH-wave landstreamer array (24-48 channels) consisting of small metal sleds with 2 horizontal 8 Hz geophones per sled (Fig. I-5), cross-connected as described in Pugin et al. (2002). Typically, receiver spacings of 0.75 m are used, though the spacing can be adjusted according to the survey targets. The short spacing of the sleds avoids spatial aliasing of the surface waves for optimum results when FK-spatial filters are applied. For P-wave surveys, one vertical 40 Hz geophone is mounted on each sled and the sled spacing is typically 1.5-3 m. These landstreamers are designed for use along paved or gravel roads.

The minibuggy minivib source (Fig. I-6) provides a low-impact, vibrating seismic source which can be operated in both P- (vertical) and SH- (horizontal) mode. The vibrating sweeps are programmable in length (seconds) and frequency range (10-550 Hz). The minivib is used to tow the landstreamer, and fitted with a distance-measuring wheel which allows the operator to move and set the source at a pre-determined source spacing. Small source spacings (typically 1.5-3 m), coupled with the small receiver spacings that are possible (and practical) with the landstreamer, allow high-fold data to be acquired. Using the landstreamer-minivib system with the typical source and receiver spacings outlined above, a 3-4 person crew can acquire 1-2 km of line a day. This is an improvement in data acquisition rates of 2-4 times over that possible with the traditional method of planted geophones.

Figure I-5: **Photo of the minivib source and SH-wave landstreamer in operation, 2006.**

Figure I-6: **Photos of the IVI mini-buggy vibratory source in operation. In the photo on the left, the minivib is being operated in SH-mode (note weight above plate in mounted horizontally.**

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