Géographie physique et Quaternaire

Sculpted Bedrock Forms along the Niagara Escarpment, Niagara Peninsula, Ontario

Formes sculptées dans la roche en place, le long de l'escarpement du Niagara, péninsule du Niagara, Ontario

Rzezbione formacje skaly macierzystej wdluz Uskoku Niagary na Polwyspie Niagara

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Résumé de l'article

On a identifié des ensembles de formes sous-glaciaires sculptées dans la roche en place (p-forms) dans des unités de roches résistantes de l'escarpement du Niagara et de l'escarpement d'Onondaga. L'échelle de ces formes est beaucoup plus grande que ce qu'on a déjà rapporté sur les formes glaciaires dans la roche en place de l'escarpement (Feenstra, 1981); nous croyons que ces formes existent dans toutes les tailles, à partir des simples marques de quelques centimètres en passant par des crêtes et des entailles décamétriques, jusqu'aux promontoires de l'ordre du kilomètre. De tels ensembles comprennent des surfaces cannelées dont l'orientation préférentielle se situe entre N40E et N45E et qui montre très peu de variation à l'intérieur d'un même site. La cartographie de ces formes a permis de se rendre compte de leur grande étendue et des difficultés de comprendre les mécanismes qui en sont à l'origine. La morphométrie des formes est semblable à ce que l'on a déjà décrit; on croit que la forme irrégulière du rebord qu'oppose l'escarpement du Niagara aux écoulements est responsable pour les formes remarquables décrites. L'enlèvement apparent de gros blocs de roche en place suppose des vitesses d'écoulement de plus de 3 m/s. Conséquemment, la sculpture des formes est attribuée à une eau de fusion sousglaciaire très rapide qui a pu avoir un débit de l'ordre de 2,1 x 10em3/s.

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SCULPTED BEDROCK FORMS ALONG THE NIAGARA ESCARPMENT, NIAGARA PENINSULA, ONTARIO

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ABSTRACT Assemblages of subglacial sculpted bedrock forms (p-forms; Dahl, 1965) are identified on resistant units of the Niagara Escarpment in the Niagara Peninsula, and on the Onondaga Escarpment. The scale of the features is much larger than previously recorded for bedrock glacial features in the Peninsula (Feenstra, 1981) and we suggest that there is a continuous spectrum of forms from small obstacle marks with dimensions of a few centimetres, through ridges and furrows measured in tens of metres, to promontories on the order of kilometres. Such assemblages comprise fluted surfaces with a consistent orientation between N40E and N45E, and which show very little variation within a site. Mapping the features has increased our awareness of their extent, and of the problems they pose for mechanisms proposed to explain them. The morphometry of the forms is similar to that described elsewhere, and the irregular edge of the Niagara Escarpment to oncoming flows is thought to be responsible for the prominent features described. The apparent removal of substantial bedrock blocks implies flow velocity well in excess of 3 m/s. Therefore the sculpting of the forms is attributed to fast flowing subglacial meltwater which may have had a discharge of the magnitude of 2.1×10^6 cumecs.

RÉSUMÉ *Formes sculptées dans la roche en place, le long de l'escarpement du Niagara, péninsule du Niagara, Ontario.* On a identifié des ensembles de formes sousglaciaires sculptées dans la roche en place (*p-forms*) dans des unités de roches résistantes de l'escarpement du Niagara et de l'escarpement d'Onondaga. L'échelle de ces formes est beaucoup plus grande que ce qu'on a déjà rapporté sur les formes glaciaires dans la roche en place de l'escarpement (Feenstra, 1981); nous croyons que ces formes existent dans toutes les tailles, à partir des simples marques de quelques centimètres en passant par des crêtes et des entailles décamétriques, jusqu'aux promontoires de l'ordre du kilomètre. De tels ensembles comprennent des surfaces cannelées dont l'orientation préférentielle se situe entre N40E et N45E et qui montre très peu de variation à l'intérieur d'un même site. La cartographie de ces formes a permis de se rendre compte de leur grande étendue et des difficultés de comprendre les mécanismes qui en sont à l'origine. La morphométrie des formes est semblable à ce que l'on a déjà décrit; on croit que la forme irrégulière du rebord qu'oppose l'escarpement du Niagara aux écoulements est responsable pour les formes remarquables décrites. L'enlèvement apparent de gros blocs de roche en place suppose des vitesses d'écoulement de plus de 3 m/s. Conséquemment, la sculpture des formes est attribuée à une eau de fusion sousglaciaire très rapide qui a pu avoir un débit de l'ordre de $2,1 \times 10^6$ m^3/s.

STRESZCENIE *Rzezbione formacje skaly macierzystej wdluz Uskoku Niagary na Polwyspie Niagara.* Zespoly podlodowcowych rzezbionych formacji w skale macierzystej (formacje typu p; Dahl, 1965) zostaly wykryte na wysokoodpornych odcinkach Uskoku Niagary na Polwyspie Niagara i na Uskoku Onondaga. Rozmiar tych formacji jest znacznie wiekszy od tworow lodowcowych poprzednio wykrytych w skale macierzystej na tym polwyspie (Feenstra, 1981). Autorzy niniejszej pracy sugeruja hipoteze, ze istnieje szerokie spektrum formacji poczawszy od kilkucentymetrowych punktow oporu, poprzez krawedzie i bruzdy dlugosci dziesiatkow metrow az do pryladkow (cypli) rzedu kilometrow. Takie zespoly skladaja sie ze zlobionych powierzchni zorientowanych konsekwentie pomiedzy N40E a N45E, wykazujacych bardzo niewielkie lokalne zroznicowanie. W czasie opracowywania mapy tych formacji zwrocilismy uwage na rozmiar tego zjawiska i na problem wyjasnienia mechanizmow jego powstawania. Morfometria formacji jest podobna do morfometrii opisanej w innych pracach. Przyczyna wielkiego rozmiary formacji jest prawdopobnie opor jaki stanowila nieregularna krawedz Uskoku Niagary dla naplywajacych strumieni wod. Widoczne usuniecie blokow skaly macierzystej implikuje szybkosc strumieni znacznie przekraczajaca 3 m/sek. Wyrzezbienie tych formacji przypisuje sie w zwiazku z tym szybko plynacej wodzie roztopow podlodowcowych ktorych rozladowanie moglo byc rzedu 2.1×10^6 m^3/sek.

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INTRODUCTION

The intent of this paper is to document a variety of p-forms[1] (Dahl, 1965) present on resistant units throughout the Niagara Peninsula, although here we concentrate on Niagara Escarpment forms. In addition we consider the implications of the features for current theories about their formation. The forms described are found along the edge of the Niagara Escarpment, usually with a few hundred metres of the edge, and they are heavily weathered by postglacial karst dissolution processes. Fresh features are found where overburden has been removed at quarries (especially at Vineland Quarries), and in addition these sites reveal smaller scale forms lost by sub-aerial weathering at naturally exposed sites.

BEDROCK AND GLACIAL GEOLOGY

The escarpment edge is primarily composed of the Gasport and Goat Island members of the Lockport Group, and the Decew limestone of the Clinton Group immediately below. In terms of lithology the Decew offers a similar resistance to the members above it and in this paper our use of the term Lockport Group should be taken to include the Decew. Other resistant members of the Escarpment which occasionally carry p-forms are the Irondequoit Limestone and the Whirlpool Sandstone. In the southern Peninsula the resistant members of the Onondaga Escarpment are the dolostones of the Bertie Formation, and the Onondaga Limestone and its associated chert beds. A detailed stratigraphy can be found in Brett and Calkin (1987).

The glacial geology is described by Feenstra (1981, 1986) with an emphasis on the various diamicton units which overlie the bedrock. The bedrock surface is far more complex than the present topographic exposures (primarily along the two escarpments) seem to indicate, as may be seen in the detailed bedrock map in Flint and Lolcama (1985). The diamict covering the bedrock is termed the Halton Till, but it is often obscured by late glacial and early postglacial lacustrine varved clays, the bottom deposits of a variety of proglacial lakes which covered Niagara Peninsula and which began with Lake Warren. Striae and erratics indicate that regional ice flow was from the northeast and that ice flowed up and over the Niagara Escarpment.

The Escarpment edge is almost always free of diamict for a variable distance ranging up to several hundred metres, and dissolution has created extensive karst pavements. To the south the surface rises to the Vinemount Moraine whose crest usually lies within a kilometre of the Escarpment edge.

THE AREAS STUDIED

Figure 1 shows the sites studied and their context within the Niagara Peninsula. It is likely that p-forms exist under diamicton close to the Escarpment edge throughout the Peninsula and will be revealed by excavation, for the Vineland Quarries, which are rich in p-forms when the diamict is stripped off, do not look promising sites on pre-excavation aerial photographs. Most p-forms occur on the massive dolomites at the base of the (Silurian) Lockport Group because it is the uppermost resistant unit composing the Escarpment, and therefore is the best exposed, but p-forms have been found on the Whirlpool Sandstone, the Irondequoit Limestone, the Bois Blanc Limestone of the Bertie Formation and the Onondaga Limestone. The former two units occasionally form extensive benches below the upper edge of the Escarpment.

PREVIOUS WORK — GENERAL

James Hall (1815) may have been the first to ascribe sculpted landforms ranging from 'details' to large scale features as large as Edinburgh's Castle Hill to large floods (tsunamis) when he described the landscape in the region around Edinburgh. Hall distinguished distinct erosional forms depending on the height to width ratio of the obstacle relative to the oncoming flow, and he drew an explicit analogy between small scale forms observed by him in streams, and examples as large as Edinburgh Castle Hill and Corstorphine Hill. In contrast, Agassiz (1840) recognized that glacial polishing of bedrock resulted in smooth and rounded outcrops down valley of Alpine glaciers. He attributed this to abrasion at the rock surface by the base of the ice which was armored with clastic material. Many authors since have associated polished and scoured surfaces with glacial processes at the rock-ice interface. However not all glacially scoured surfaces can be attributed to this alone. Many of the forms that are attributed to subglacial bedrock erosion appear to be much too complex, intricate and small scale to have been ice scoured, and the forms lend themselves as easily to other explanations. Given the wide variety of forms it is not surprising that more than one process has been proposed in the literature and although ice scouring was the first process attributed to the creation of 'plastically sculptured' p-forms (*sensu* Dahl, 1965), Andrews (1883) in a descriptive account of features now recognized as p-forms in the Laurentian Hills, attributed their unusual form to both water and ice. Chamberlin (1888) concluded that many of the larger scale surfaces were glacially modified preglacial features, but he allowed that more sinuous features could be the product of subglacial streams, as did Wright (1889). The idea that subglacial meltwater created the general class of forms was not seriously proposed until Ljungner (1930). Ljungner concluded that both ice and water were involved in the formation of the forms, but that their morphology was primarily the result of high velocity, turbulent, subglacial meltwater. Hjulström (1935) supplemented Ljungner's position with the inclusion of cavitation as a major erosive force for he argued that any roughness caused by intensive cavitation would be smoothed away by sediment loads within the flowing water. Another alternative theory was advanced by Edelman (1949, 1951) who suggested that a slurry of 'ice-water paste' would provide sufficient abrasive power, when combined with rock flour, and would prove flexible enough to produce p-forms. Most subsequent researchers have dismissed Edelman's slurry as the major component in p-form development (Dahl, 1965; Bernard, 1972; Allen, 1971, 1984). A similar and more detailed suggestion was made by Gjessing (1965). Recent work by Sharpe and Shaw is detailed below in the discussion section, and attributes the features to high velocity sub-glacial meltwater.

1. The revised version of this paper was submitted before we saw the paper by Kor, Shaw and Sharpe (1991) which recommends the term *s-form* (sculpted form) instead of *p-form* (plastically moulded form). We endorse that change in terminology.

Kor, P. S .G., Shaw J. and Sharpe, D. R., 1991. Erosion of bedrock by subglacial meltwater, Georgian Bay, Ontario: a regional view. Canadian Journal of Earth Sciences, 28: 623-642.

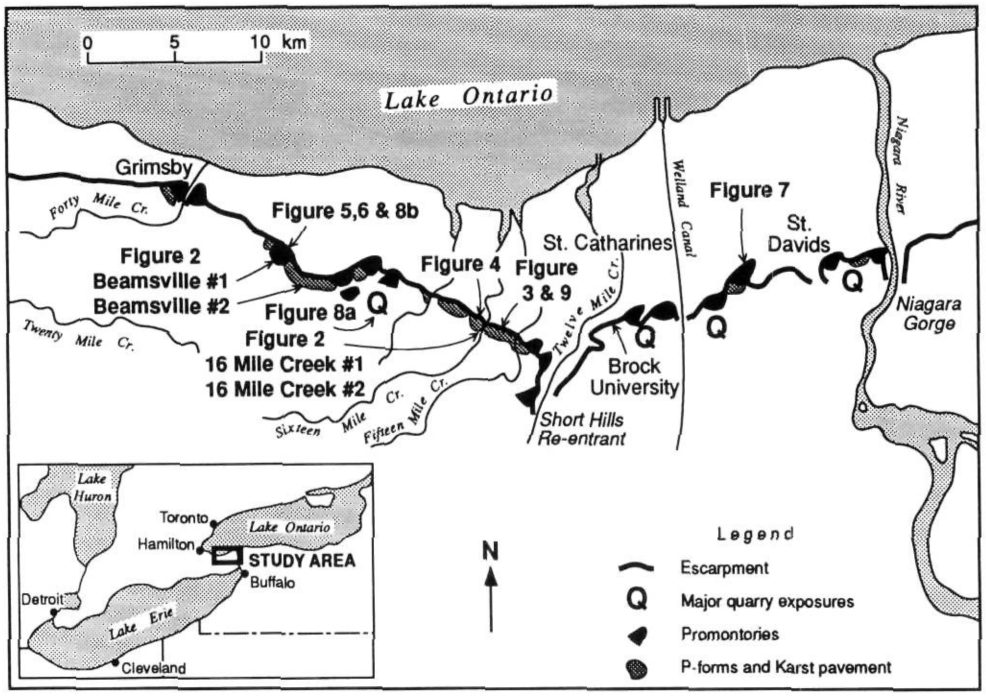


FIGURE 1. Location map indicating areas with extensive p-forms, the location of promontories, and the sites of quarries.

Carte de localisation montrant les emplacements des grandes formes sculptées (p-forms), des promontoires et les sites de carrières.

PREVIOUS WORK — NIAGARA PENINSULA

Within the Niagara Peninsula p-forms have been reported by several previous authors, although never with that name. Hall (1843) and Lyell (1845) both give clear descriptions of grooves or furrows, striae, and obstacle marks (for definitions see Allen, 1984; Sharpe and Shaw, 1989), and remark that workers in Western New York found glacial grooving on resistant units at all levels on the Escarpment near Lewiston. Chamberlin (1888, Figs. 21 and 22) illustrates two small obstacle marks which were found by G. K. Gilbert near St. Davids and removed to the Smithsonian Institute. A modern reference show pictures of small obstacle marks, attributed to high velocity water flow, found on the Escarpment south of St. Catharines (*e.g.* Terasmae *in* Prest, 1983, Fig. 21d, also Shaw and Sharpe, 1987b, Fig. 2), and we believe that is likely that some of the glacial striae indicated by Feenstra (1981, 1986) are small p-forms of one type or another.

Elsewhere within the Lake Ontario basin p-forms in Trent limestones have been identified, and these are medium scale forms with an extreme relief of no more than one to two metres and transverse wavelengths of about 10 m between ridges (Shaw, 1988). Very large scale forms are recognized by Shaw and Gilbert (1990, their Fig. 2) who describe 'escarpment noses' along the north shore of eastern Lake Ontario and also submerged in the same region. Otherwise no very large scale forms have yet been recognized in the literature, with exception of the large re-entrant valleys, such as the Short Hills re-entrant west of St. Catharines and the Dundas Valley re-entrant, which are attributed primarily to ice-gouging by through flowing high velocity ice streams (Straw, 1968). Straw payed little attention to the headlands, which he termed *'promontories'*, separating the re-entrants, although on his Figure 8 they are highlighted to display a rounded appearance facing up-flow, and he identified Coffin Hill on the south side of Owen Sound, amongst others, as a *'huge rock drumlin'*.

TERMINOLOGY

To avoid confusion we have tried to be consistent with the reports of recent workers such as Shaw (1988), Sharpe and Shaw (1989) and the schematic diagram in Prest (1983, Fig. 22). In earlier literature (Hall, 1843; Lyell, 1845; Wright, 1889; and many others) the terms *glacial grooves* or *glacial furrows* correspond to the modern term *p-forms*, although Chamberlin (1888) uses the terms *fluting* and *fluted hills*. The positive relief features we describe are morphologically similar to till flutes as described by Boulton (1973), but as they cannot result from the same process we term our features *remnant ridges* or *rat-tails* (positive relief) and *furrows* (depressions, negative relief). The former correspond to the term *tadpole rock* (*French: rocdrumlin*) proposed by Dionne (1987). The whole suite of forms, at all scales we describe is termed a *fluted surface*. This includes a range of minor forms such as cavettos, obstacle marks and spindles which are described below. In fluvial literature (Maxson and Campbell, 1935; Allen, 1970) *flutes* refer to shaped and eroded rock depressions between relative topographic highs. In our descriptions and discussions the meltwater eroding the forms is assumed to come from the northeast on account of the streamlined forms revealed at nearly all scales, with the blunt ends facing the northeast and the remnant tails pointing to the southwest.

METHODOLOGY

Most of the forms described here were located by walking along the Escarpment edge, although promising areas sometimes can be seen from aerial photographs. The best series is that of 1972 at a scale of about 1: 12,600 which was taken before summer foliage developed. Even so, only large scale features can be seen, and trees often hinder efforts to photograph the features at ground level. Measurements were taken with a tape, Suunto handlevel, and light levelling staff. Directions were taken with a Suunto hand compass by sighting along the central axis of flutes, or along their straight margins if there was no obvious planimetric tapering. Values are estimated to be correct to $\pm 2°$ and reported values have been corrected to true north by subtracting 10° (a best estimate of magnetic deviation for 1990) from the field readings. All grid references are within the 100 km square denoted by PT in UTM Grid Zone 17T.

KARST DISSOLUTION

Nearly all the naturally occurring forms we describe have been strongly affected by postglacial dissolution processes, and the Escarpment edge is characteristically a limestone pavement whenever rock is exposed at the surface. We are confident that the greater proportion of the dissolution is postglacial for we have seen no examples of till injected into preexisting grykes or trenches in quarry exposures, although they are reported at Vineland Quarries (D. R. Sharpe, 1991, personal communication). We have measured grykes to average 0.63 m wide and 1 m deep. Trench karren are occasionally seen and may be enlarged to as much as 1 to 1.5 m wide (Pluhar and Ford, 1970). Grykes and trenches bear no apparent relation to the forms we describe. Exposures provided at Vineland Quarries and by building projects such as at Brock University Schomm Tower loading bay (425755), and the stream re-alignment at the Staff Farm near Louth Conservation area on 16 Mile Creek, reveal fresh p-forms, often in close juxtaposition to evidence of dissolution having proceeded under a shallow vegetative mat (339754). Finally, at one locality south of Beamsville (Fig. 2, Beamsville #2, 245778) a huge clint block of dolomite (2.5 m $\times$1.5 m $\times$ 2 m) has been stranded athwart a flute, and the rock beneath it has been preserved with only very limited dissolution (< 1 cm). In the very centre, faint striae may still be seen. Profiles measured along the flute away from the block imply a mean surface lowering of about 15 cm during the postglacial.

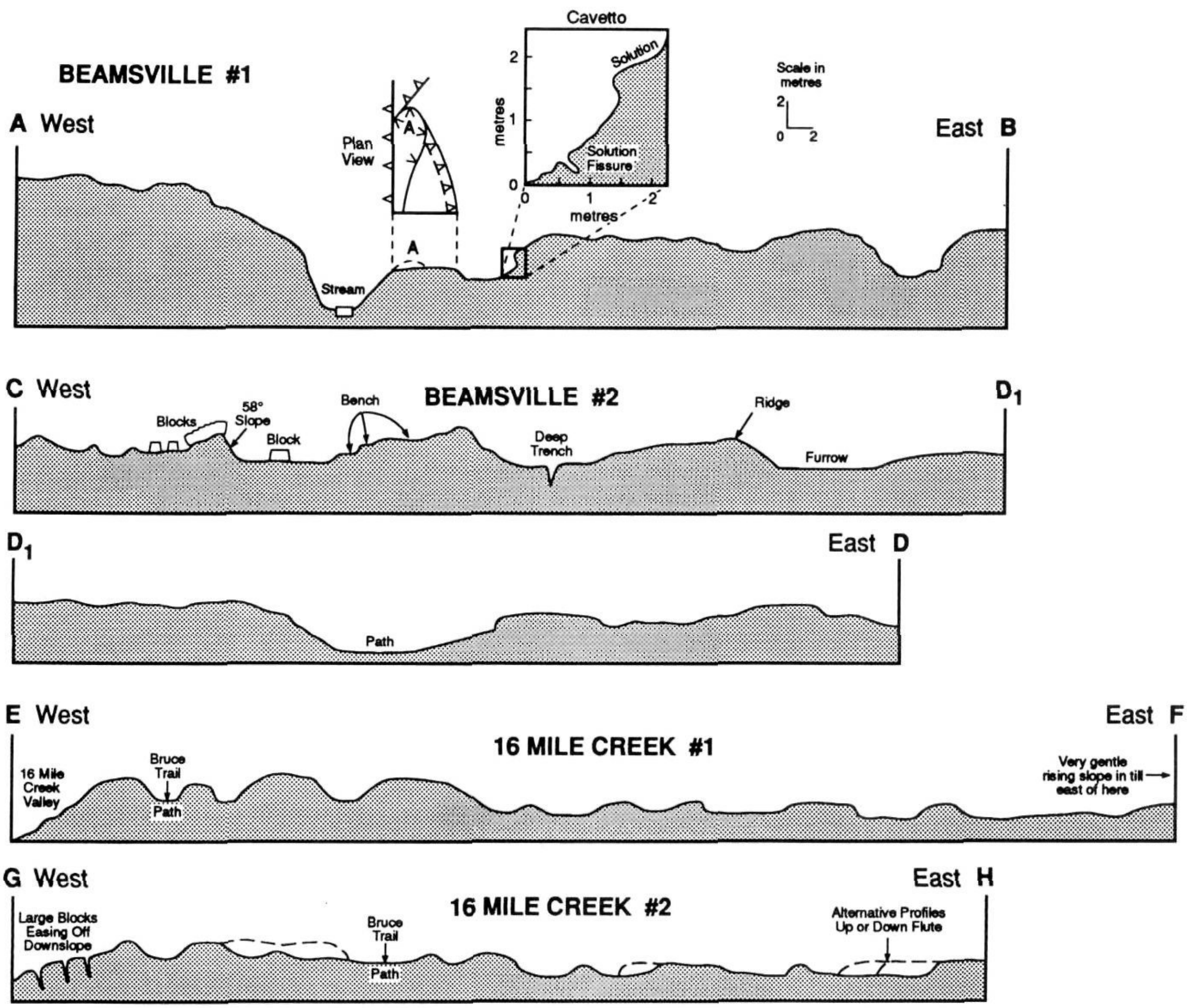


FIGURE 2. Profiles of the fluted surface at Beamsville and Sixteen Mile Creek.

Profils de la surface cannelée de Beamsville et de Sixteen Mile Creek.

STRIAE

Feenstra (1981, 1986) mapped striae in the Peninsula. At fresh exposed sites, striae (elongated narrow scratches with millimetre dimensions) may still be seen engraved on the polished surface. They typically have an orientation which is 10 to 15° more northerly than the main trend of the fluted surface. On occasion they are seen to pass through furrows, still oblique to the general trend of the fluted surface.

P-FORMS OR FLUTED SURFACES

It is as well to preface this discussion of form by James Hall's remark (1815, p. 179) that "where a firm rock of any kind has been exposed to the action of a rapid river, its surface acquires in consequence of that abrasion a peculiar character, which every one recognizes at a glance, but which is difficult to describe in words". Holistic characteristics are hard to describe, and the terms used below are not hard and fast definitions but rather guides to the identification of the more salient features in the landform assemblage.

FLUTED SURFACES — AN ASSEMBLAGE OF FURROWS, REMNANT RIDGES AND MINOR FORMS

Furrows and remnant ridges taken together as a fluted surface appear as irregular undulations along the edge of the Niagara Escarpment, normally with a vertical amplitude of about 0.5 to 2 m rising on occasion to 5 m. Their most noticeable characteristic is the remarkable and consistent elongation in the orientation NE to SW. Figure 1 marks all sites where we have identified examples. Figure 2 shows cross-profiles at four sites. The upper surface of a ridge is normally fairly level transverse to the flow direction and along it. Mean wavelengths at four sites are measured as 10.25, 8.75, 8.75 and 8.9 metres, a wavelength being measured as the distance between the centres of adjacent ridges transverse to the flow direction. In areas with stronger relief there may be ridges superimposed on others, and in places small scale forms have been lost through karst dissolution, and from the disruption of clint blocks by tree-throw, especially at the margins. The sides of ridges are usually steep, >30° and rise directly to the upper surface, although in the case of the larger ridges there are sometimes intermediate benches which might equally be regarded as one sided furrows (Figs. 2 and 3).

The longitudinal profile of a ridge is normally fairly level, and if there is a noticeable slope it is usually down-flow (*i.e.*, to the SW). Occasionally a ridge will terminate or be interrupted downflow abruptly with a transverse steep slope (Fig. 4), as if the remaining section downflow has been stripped or plucked away. However, in the case of Figure 4 the remaining ridge downflow shows signs of sculpting and the existence of secondary rises in the profile downflow of it indicate that the abrupt break was not the terminal event. There is a secondary rise towards the end of the rat-tail in Figure 3. The upflow nose is normally bluntly rounded in plan and rises steeply to the main upper longitudinal level of the ridge (Figs. 3 and 4), although many upflow noses of ridges have been severely damaged by tree throw following dissolution of blocks along joints and bedding planes. Ridge orientation is characteristically in the range N40E to N45E with much less deviation at a particular site. The ridges, as positive topographic forms, draw attention to themselves, but the flat rock-floored furrows that lie between them are just as marked. Their floors tend to rise down flow and they are most evident close to the escarpment edge. On occasion ridges are found within the furrows, especially close to the escarpment edge, and multiple superimposed forms are not uncommon (see Fig. 2, Beamsville #1).

Some of the furrows carry some spring meltwater flow by virtue of their lower topographic position and north-east slope, but there are only rarely signs of distinct stream channels. When water is fed to the escarpment edge from a stream basin on the till slopes of the Vinemount Moraine to the south then a stream will occupy a furrow and the stream may cut a gorge as it crosses the escarpment edge. In nearly all cases the fluted surface seem to have directly influenced the orientation of streams crossing the escarpment. The clearest large examples are perhaps Sixteen Mile Creek and Forty Mile Creek, but there are many small scale ones.

Figure 5 is a stereogram of a strongly fluted surface south-west of Beamsville, and Figure 6 is based upon it. The figures illustrate the complex relationship of the fluted surface to the ridges and furrows of which it is composed. We have marked also the secondary escarpment below, capped by Irondequoit Limestone and which displays a sympathetic trend to that outlined by the blunt nosed ridges developed in the overlying Lockport Group (Fig. 7). Because none of the furrows carry a large stream this fluted surface remains intact. However, it is likely that a somewhat similar system was bisected, and then greatly enlarged and overdeepened by Forty Mile Creek, to give rise to the twin promontories overlooking Grimsby (165825).

TAPERING FORMS

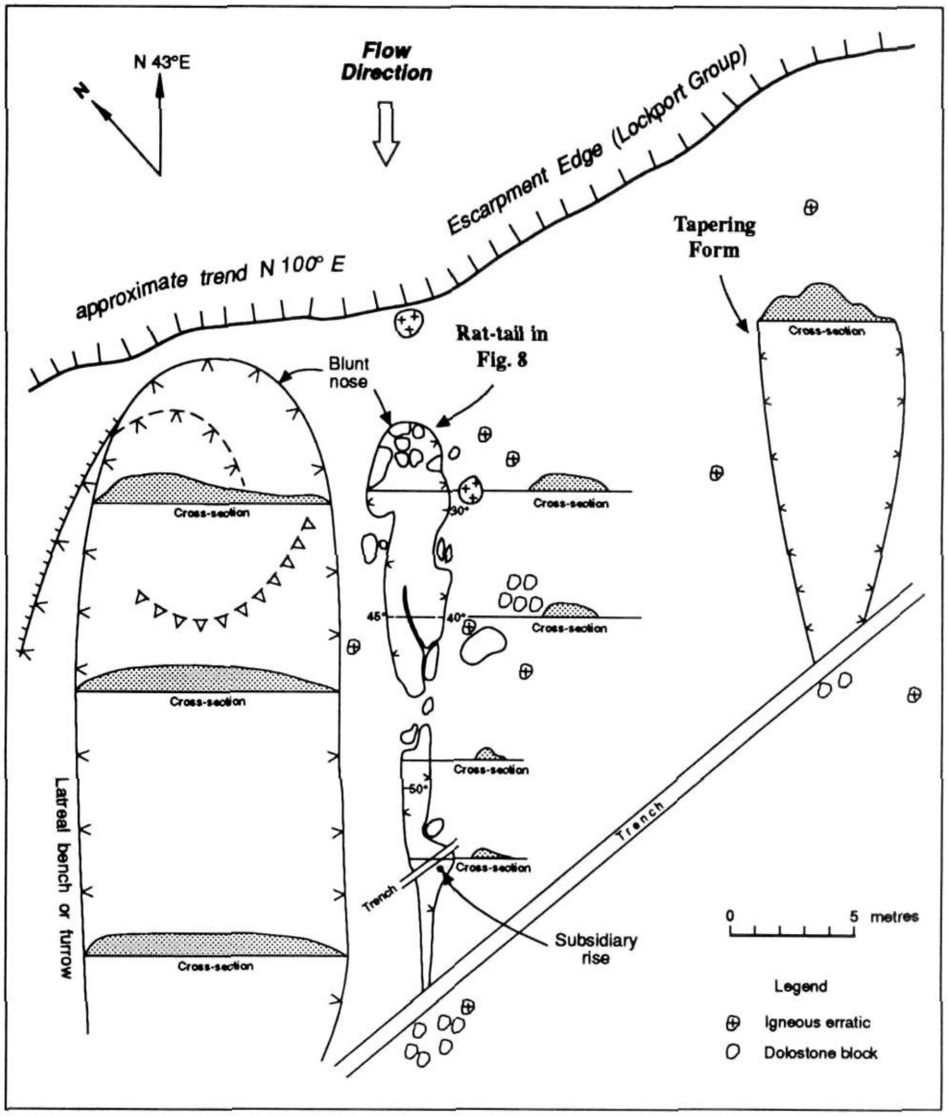
Some of the large ridges show planimetric tapering in the direction of regional flow reminiscent of the obstacle marks and rat-tails described at Cantley, Québec (*e.g.* Shaw and Sharpe, 1987b; Sharpe and Shaw, 1989). A few in particular have well-defined rat-tails associated with them. Figures 3 and 4 are maps of particularly noteworthy examples of large rat-tail features, 18 m and 53 m long respectively, and Figure 8 is a photograph of the rat-tail in Figure 3. The scale and orientation of these features is similar to the ridges to which they are adjacent, except that they are narrower. Both the rat-tails display secondary rises along the ridge well downflow from the primary nose. Long profiles demonstrate the existence of small subsidiary rises at 32 m and 50 m from the nose of Figure 4, and 18 m from the nose of Figure 3. Knife-edge forms, seen on Figure 3, and on a feature adjacent to Figure 4, but not mapped here, have been seen.

PROMONTORIES

At several localities the escarpment has been shaped into distinct promontories facing up-flow (Fig. 1), of which the most striking example is the one at Woodend (500790) overlooking the Queen Elizabeth Way as it begins to surmount the escarpment (Fig. 7). The west side, facing the northwest is steep, 30°, and is remarkable for the virtual elimination of the Irondequoit ledge. The Irondequoit is not seen exposed, although a slight flex in the slope profile indicates its position. On the opposite

FIGURE 3. Map of p-forms east of Sixteen Mile Creek, including a rat-tail form, tapering forms, lateral benches or furrows, and blunt noses.

Carte des formes sculptées (p-forms) de Sixteen Mile Creek, comprenant une forme en queue-de-rat, des formes en fuseau, des formes en entailles et des formes au front aplati.



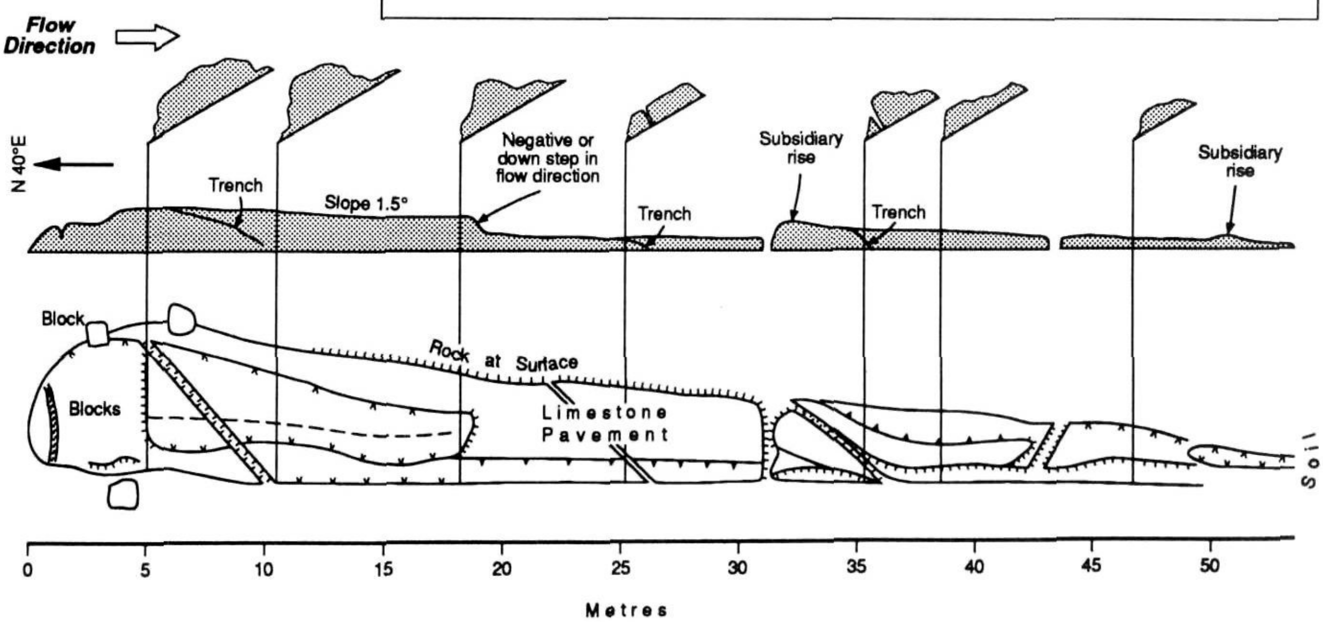


FIGURE 4. Map, profile and sections of large rat-tail on the Staff Farm, west of Sixteen Mile Creek.

Plan, profil et coupes d'une importante queue-de-rat à la ferme Staff, à l'ouest de Sixteen Mile Creek.

side the Irondequoit bench develops from nothing to 40 m wide within 200 m and persists until it is masked by the rising till ramp. If the Irondequoit is ignored this side has an identical slope to the northwest side. The upper surface of the promontory at the upflow end carries a fluted surface with a ridge wavelength of about 8-12 m, and with one strong furrow rising from the slope below the nose. Other promontories are less completely isolated but are no less distinct, they are marked on Figure 1. The Beamsville example described (Figs. 5 and 6) may represent a stage in the development of a promontory, and there is a similar if less pronounced situation east of Sixteen Mile Creek (355755).

CAVETTOS

One distinct preserved cavetto (a distinct channel cut into a vertical rock face causing an overhang) has been found naturally exposed along the escarpment south west of Beamsville (Fig. 2, Beamsville #1), and the location of this section is marked on Figure 6. It can be seen that this form overhangs itself almost like one half of a horizontal pothole (Fig. 9a), and it occurs opposite a small ridge which seems to have diverted flow against the wall opposite to erode the cavetto. Many other steep sections show signs of this form but are too degraded by dissolution for positive identification, for example, the steep western side of the rat-tail in Figure 4 may have carried small cavetto forms originally, and there are near vertical sides at Beamsville #2 (Fig. 2). At Vineland Quarries many smaller cavettos have been found and one form approaches the size of the naturally exposed feature (Fig. 9b). The quarry sites show cavetto depths as small as 5 cm while the natural site shows a depth of almost 40 cm. It is surmised that only the largest features can still be recognized in the natural sites.

SMALL OBSTACLE MARKS

When a fluid is diverted around a solid obstacle the acceleration of flow cuts lateral furrows and leaves in the wake of hte obstacle a tail of remnant rock, or in a soft sediment system a slack water deposit. Obstacle marks are described (though not named) by Chamberlin (1888) at the St. David's quarry (560795), and at St. Catharines by Terasmae in Prest (1983, Fig. 21(d); Shaw and Sharpe, 1987b). They have now been quarried away or covered by landfill, but their identification is not in doubt as they are very clearly illustrated. We have located

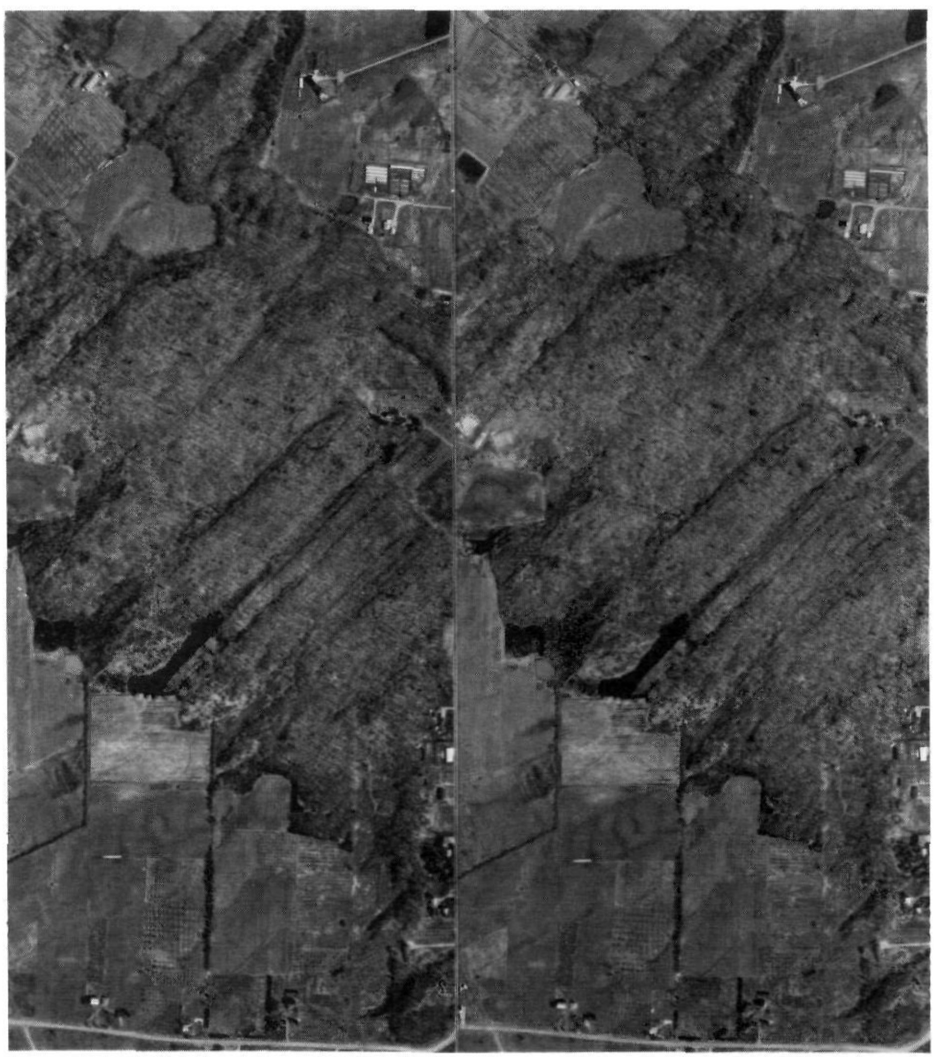


FIGURE 5. Air photograph stereogram of a developing promontory southwest of Beamsville (72023, photographs Nos. 65 and 66; published by permission). Same scale as Figure 6.

Stéréogramme d'un promontoire en formation au sud-ouest de Beamsville (72023, photos n^{os} 65 et 66, droits de reproduction obtenus). Voir l'échelle de la figure 6.

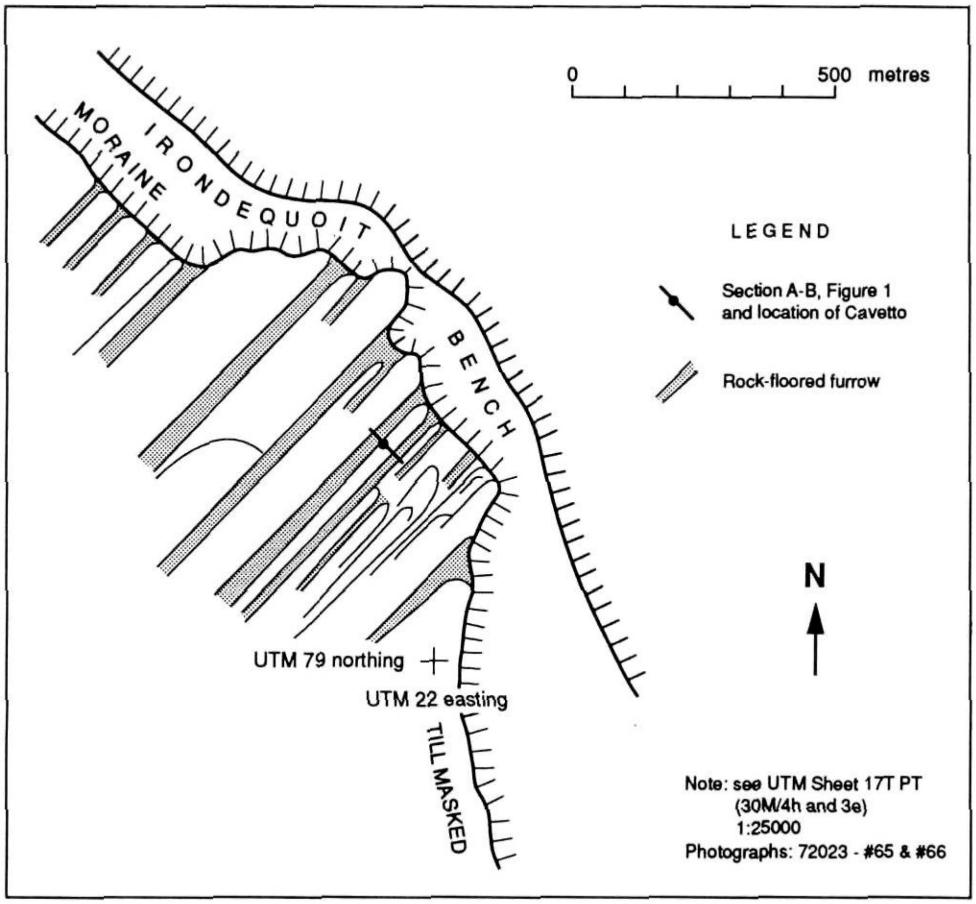


FIGURE 6. Map from aerial photographs of a developing promontory southwest of Beamsville (based on Fig. 5).

Carte issue des photos aériennes du promontoire en formation de la figure 5.

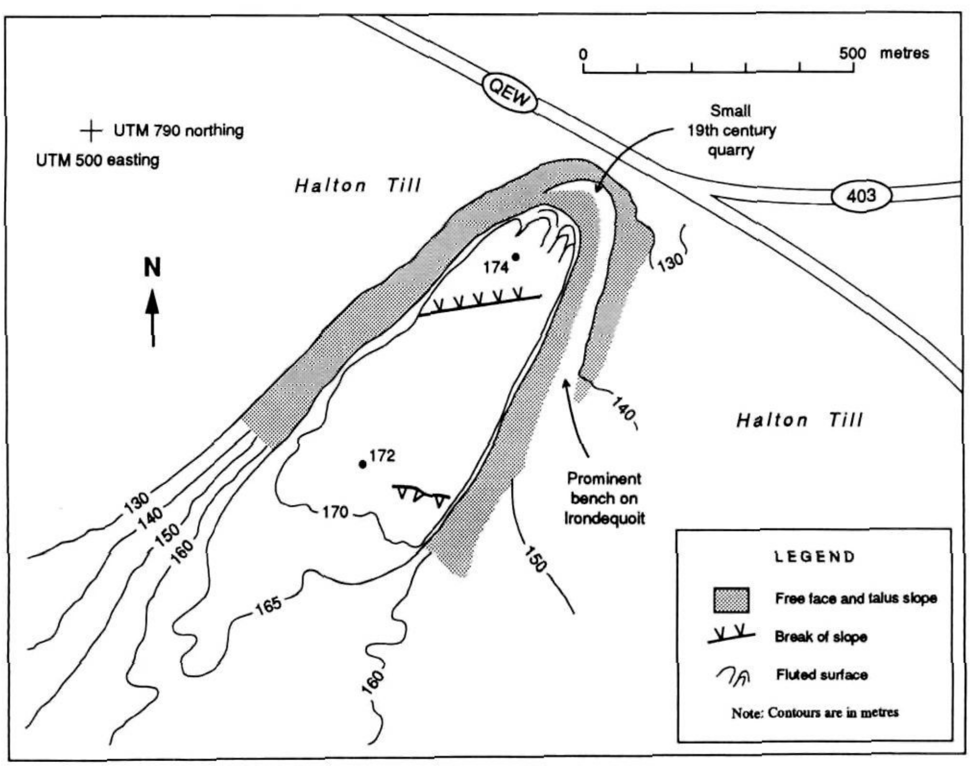


FIGURE 7. The isolated promontory at Woodend, with a well developed bench on the south-east face.

A Woodend, promontoire isolé, avec gradin bien développé sur sa face sud-est.

FIGURE 8. Rat-tail feature mapped in Figure 3. Notice the pronounced curve to the tail. There is a subsidiary rise where the observer is standing (photograph by R. E. Stenson).

La forme en queue-de-rat cartographiée à la figure 3. Noter la courbe prononcé vers la queue. Il y a une élévation secondaire là où se tient le personnage (photo de R. E. Stenson).

one example on a triangle of exposed rock at an access point to the Highway 403 immediately south-west of the Walker Brothers' quarry in St. David (553786). It is 15 cm wide, it rises 2 to 3 cm above a surrounding plane surface, and its identity is maintained for about 1.5 m downflow. We are aware also of extensive swarms of obstacle marks (probably the *glacial striae* marked by Feenstra, 1986) in the abandoned quarry on Quarry Road (384488), west of Port Colborne on the flat lying bench of the Bertie Formation at Port Colborne, and there are small examples at Rock Point Provincial Park on Onondaga Limestone (190444). They are normally < 1 m in length and a few centimetres wide. Vertical relief is normally one to three centimetres (relative to the lateral furrows) and the obstacles are provided by corals. In an abandoned quarry south of Vinemount (087809) a slightly larger feature was recorded; 2.2 m × 0.6 m, with a relief of 2 to 3 cm and flanked by broad shallow lateral gooves. It is oriented N16E.

SPINDLE

A spindle is a variety of furrow (Shaw, 1988), looking much like the elongated impression of a smooth tire in mud. A large spindle 4 m long, 30 cm deep and approaching 1.5 m wide has been located on the resistant Whirlpool Sandstone between 17th and 19th Streets Louth close to Vineland (333770). The entrance is oriented N64E and the exit is N42E with a mean trend of N53E, 10° more easterly than is usual on top of the Escarpment, and with a greater variation in orientation.

GENERAL CHARACTERISTICS

The p-forms have the greatest relief closest to the escarpment edge, or wherever there is a distinct rise in the topography such as is afforded by the vertical addition of another resistant unit in the Lockport Group. At Beamsville the rise at the escarpment edge from the rock-floored furrow to the upper surface of adjacent rock ridges may be in excess of 4 or 5 m, but this difference is eliminated two or three hundred metres downflow.

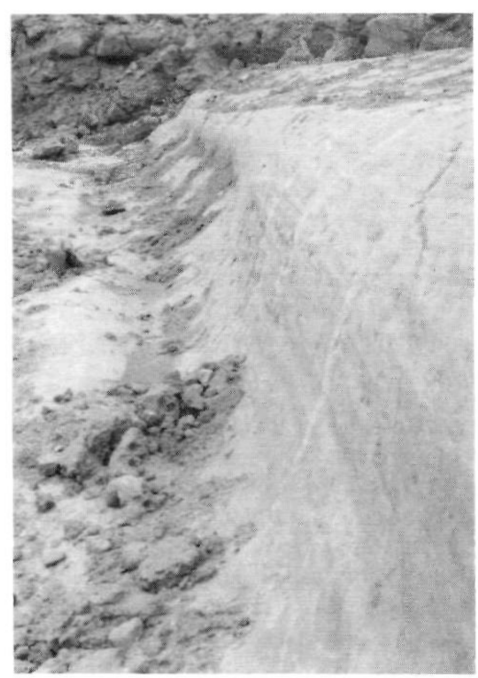


FIGURE 9. A. Preserved cavetto with overhang south-west of Beamsville. The measuring stick is 1 m high. B. Fresh cavetto exposed in Vineland Quarries, similar to (A) (photograph by R. E. Stenson).

A. Au sud-ouest de Beamsville, cavet bien préservé avec surplomb. Le bâton mesure 1 m. B. Cavet non altéré, à découvert dans la carrière Vineland, semblable à (A) (photo de R. E. Stenson).

Normally the floor of the furrow rises downflow whereas the slope of the ridge remains constant or even declines slightly downflow, for it is not uncommon to find negative relief steps in the down flow direction (like lee-side plucking on a roche moutonnée) where a layer of rock has been stripped off the ridge downflow of a joint. It is rare for an individual feature to retain its identity over the entire distance to the diamict cover, for the edge of the ridge will often be benched for a distance and the furrow floor may contain small ridges (Fig. 2, #1). Overall, however, the relative relief observed reduces downflow.

When blunt-nosed ridges begin downflow of the escarpment edge there are occasionally signs of over-deepened proximal and lateral furrows, as typically occurs around obstacle marks (Hall, 1815; Allen, 1984). Because the focus of dissolution processes enriched by organic acids from the forest litter will be at the margins of the ridges, we hesitate to identify such features as definitely present at natural exposures. However, in air photographs of Vineland Quarry in 1972 (Series 72023, photos #111 and #112) clusters of blunt-nosed features are fronted by proximal scours, filled with water in the photograph.

The most striking morphological feature of the fluted surfaces is their elongation, and the parallelism of the edges. It is rare for an edge to depart by more than 5° from others in the immediate neighbourhood, and at all sites measured the mean direction is very steady in the range N40E to N45E. The only exception is the small feature discovered well to the west of our main area. Although elongation is very noticeable it is not easily quantified for a large sample because individual features slowly merge their forms with adjacent ones. For the two separate standing rat-tails (Figs. 3 and 4) elongation is about seven times the maximum proximal width. It is reasonable that this ratio holds for the fluted surface as a whole.

In fresh exposures a characteristic smooth polished surface is evident. It is noteworthy that no evidence remains of the clastic load normally thought necessary for the production of worn rock surfaces. Where sections are seen the immediate overburden is typically a clay or silty clay with occasional clasts.

DISCUSSION

We have demonstrated that fluted surfaces are widely distributed along the edge of the Niagara escarpment, and also are abundant to the south of it when revealed by stripping of the overburden. They are also present in a subdued form on other resistant Escarpment members such as the Irondequoit Limestone, the Whirlpool Sandstone, and on the resistant units of the Onondaga Escarpment in the south of the Peninsula.

SCALE OF FORMS

We are not aware of any distinct break in the spectrum of forms and it is our belief that the forms are essentially self-similar from the size of centimetre wide obstacle marks at least up to the size of the 'promontories' described by Straw (1968) north of Hamilton which can be kilometres wide, and tens of metres high. Essentially the same point was made by Shaw and Sharpe (1987b) in discussing an erosional origin for drumlins, some of which were rock cored. A wide range of scale is also evident in Shaw and Gilbert (1990). Figure 10, which is based on measurements from Figure 2, augmented by other field measurements supports this notion. However, we emphasize that the sample is not random. We have plotted height against width, and we have neglected length because with most of the forms there is great difficulty in deciding where a feature loses its identity downflow. The only very marked break in the spectrum is towards the low end and this probably reflects the fact that small scale forms (<1 m wide) have weathered away in natural exposures, where we estimate surface lowering to be about 15 cm, but with considerable local variation. A more or less continuous spectrum of sizes might be expected from an erosional process which erodes a ridge from each side, *i.e.*, by a fluid flowing around obstacles of various sizes as a consequence of varying bed roughness.

INTERPRETATION OF THE FORMS

The forms we have described are consistent with the features described by Shaw and Sharpe (1987a, 1987b), Shaw (1988), Sharpe and Shaw (1989), Shaw and Gilbert (1990), and attributed by them to meltwater flow. There are also strong morphological resemblances to forms (both erosional and depositional) described by Allen (1984) for the case of fluid flows charged with varying amounts of sediment. Thus we propose to discuss the genesis and development of the fluted surfaces in terms of sediment charged fluids. Because of the position of the escarpment athwart the direction of regional ice flow (Feenstra, 1986) it would appear that subglacial meltwater is the only reasonable source for such a fluid, especially one which has acted regionally upon the escarpment. An interesting, although unsubstantiated, alternative may be provided by a superflood (Huggett, 1989) but it is not assessed here in the absence of any useful controls.

It is our opinion that the fluted surfaces correspond to assemblages of the features termed erosional longitudinal ridges and furrows, such as those described by Allen (1984)

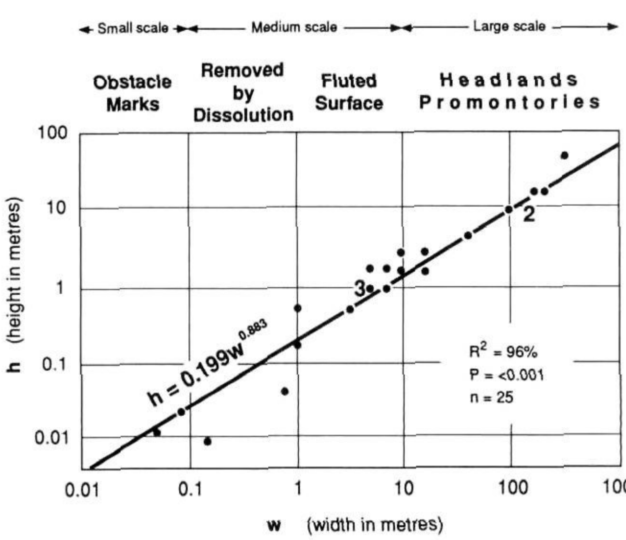


FIGURE 10. Graph of height against width for p-forms along the Escarpment. Numbers indicate multiple records.

Graphique de la hauteur sur la largeur des formes sculptées le long de l'escarpement.

from a wide range of environments (tidal, fluvial, aeolian, and deep sea), and allowing that this assemblage includes obstacle marks, or scour remnant ridges, as end members of the erosional series. Allen describes the wavelength (the mean spacing of ridge crests transverse to flow) of such erosional grooves and furrows as ranging from a few centimetres to two kilometres depending on the environment in question. Because the features we describe begin at the escarpment edge where the meltwater would first encounter an obstacle we also expect that upflow noses will be shaped roughly in accord with those for obstacle marks as described by Allen (1984). In his analysis *longitudinal grooves and furrows, obstacle marks or scour remnant ridges*, and rat-tails are all indicative of secondary flow organized into a series of rotating vortices with axes aligned along the primary flow direction. Any adjacent pair of vortices are counter-rotating.

WHERE ARE THE OBSTACLES?

If, as we have argued, there is a continuous spectrum of forms the question arises, because small obstacle marks are so clearly related to clearly defined obstacles, such as fossils or chert nodules, what is the 'obstacle' for the much larger forms? In our view the obstacle was the irregular edge of the Niagara Escarpment presented to oncoming flows. At present the dismemberment of the massive dolostones by dissolution along joint lines, usually to an observed depth of at least 1 to 2 m, makes it is inconceivable that these same units could avoid being readily removed by overriding ice. This would lead to the removal of a layer of rock of equivalent thickness (1-2 m) during glacial advances (either by glacial ice or by the subglacial meltwater), over a zone extending up to several hundred metres away from the escarpment edge. After the removal of surface weathered blocks there would still be an irregular profile of resistant rock presented at the escarpment edge, transverse to flow. This profile would likely preserve a muted topographic echo of any previous fluted surface profile, and especially for the larger cases such as promontories. In any case the surface profile would be stepped in form, reflecting the regularly bedded dolomites and limestones of the Lockport Group.

MELTWATER MEETS THE ESCARPMENT

Meltwater confined beneath ice, encountering the escarpment, would be forced up and over it, and an irregular bedrock profile transverse to the flow direction would cause it to adjust its flow laterally around highs and into lows, developing vortices as it did so. Charged with abrasive sediment meltwater would erode the rock surface and adjust the gross form to one more streamlined. As the vortices spread and dissipate downflow converging flow lines may cause tapering of edges away from the mean flow direction. According to Allen (1984) such flow lines diverge no more than 5° or 10° from the mean axis of flow. After substantial erosion of the rock surface, vortices on either side of isolated remnants would erode rat-tail features. Vortices directed persistently sideways against rock faces would develop cavettos.

Ridges with more or less parallel sides, a common situation, may be produced by vortices with opposite rotations, but we recognize that how the exact morphology of rock ridges relates to the vortex rotation will require considerable experimentation which is not undertaken here. Allen (1984) notes that the origin of erosional furrows and ridges is obscure. However, he attributes and photographs straight-sided eroded mud ridges in the Severn Estuary, and straight downflow sand lines to counter-rotating vortices. Meltwater provided with an abrasive load might simulate such behaviour, just as sand provides the erosive tool in the marine environment.

It is to be expected also that the flow disturbance and vortices introduced by the escarpment edge will be dissipated downflow and away from the edge, and therefore, that there will be much more subdued forms in this region. The forms we have seen appear to have less relief downflow from the edge, and often lose their identity within two hundred metres of the edge where, in any case, they usually disappear beneath the Vinemount moraine. The rising floors of the furrows, especially pronounced close to the escarpment edge, are primarily responsible for this loss of relief, for the ridge surfaces are frequently rather level except where a superimposed structure is seen. The rising furrow floors therefore signal the dissipation of energy downflow, and a reduced erosive capability.

ASYMMETRY

Some features are noticeably asymmetric. Figure 11 illustrates how an approximate pattern of vortices may be reconstructed for the two conspicuous rat-tails, in both cases with a degree of asymmetry. For Figure 4, it may be inferred that flow lines from the vortex on the east moved up and over the rat-tail. On the west side of the ridge the vortex produced a relatively straight sided steep wall with just discernable scour

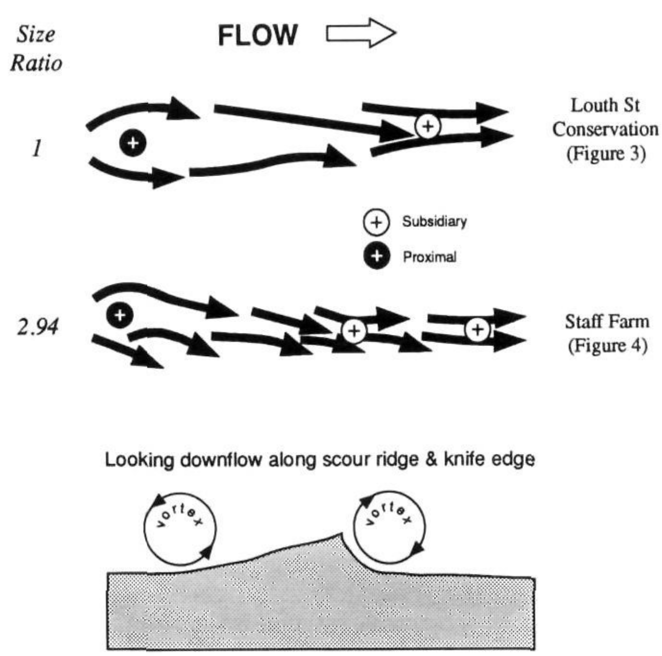


FIGURE 11. Diagram to illustrate the probable flowlines over the two rat-tail features mapped. Size ratio indicates differing scales of original features. The reason for the asymmetry is unknown.

Diagramme illustrant les lignes d'écoulement probables sur les deux formes en queue-de-rat cartographiées. Le chiffre à gauche donne la différence d'échelle entre les deux formes. On ne saurait expliquer l'asymétrie.

patterns in plan. Presumably the two vortices met over the centre of the rat-tail, a situation that could give rise to knife-edge forms, seen on Figure 3, and on a feature adjacent to Figure 4, but not mapped here. Subsidiary rises, possibly arising after an upper layer or rock had been stripped off (Fig. 4), caused an additional separation of flow into paired vortices.

At a much larger scale an asymmetry is seen on the promontory described at Woodend (Fig. 7). In this case the wide bench developed on the Irondequoit Limestone is interpreted to be the lateral furrow cut as flow diverged around the nose. It indicates that flow depths may have been as great as 30 m, for a fluted surface is also found right at the north eastern tip of the upper surface, and a furrow rises from the slope below to bisect the nose.

The asymmetry is puzzling, but it is found at all scales, for small obstacle marks often have one lateral furrow preferentially developed over the other, a situation also reported by Shaw *et al.* (1989). One possibility is that asymmetry arises from relatively tiny initial imbalances when water meets an obstacle, and that it then grows by positive feedback. Another is that it signals small shifts in the mean flow direction of the main water body so that one side is favoured over the other. We have not encountered any specific studies of asymmetry for the forms we describe.

FLOW CHARACTERISTICS

It is difficult to characterise the flow in detail other than to infer that flow depth may have been at least as deep as the maximum relief on the fluted surface, typically up to five metres. At Woodend the large lateral furrow (bench) and the upper fluted surface might imply a flow depth as great as 30 m. Rock layers stripped off the top of ridges, whose surfaces have then been scoured (Figs. 3 and 4), implies water flow over them. The general parallelism of edges suggests a sheet flow, for a tube-like flow of water might be more inclined to meander whatever its velocity. The smoothly polished surface implies abrasive wear and therefore a clastic load in the meltwater, no evidence of which remains. There is no direct evidence upon which to base an estimate of flow velocity, but we observe that the stripping of limestone and dolomite blocks will likely involve blocks with maximum dimensions up to several metres wide and long, and up to a metre thick. Casual inspection suggests that Twenty Mile Creek, with flow velocities in some reaches up to 3 m/sec., does not transport blocks of that calibre, although blocks with maximum dimensions up to a metre are fairly readily moved. The implication is that meltwater velocities were substantially above 3 m/sec., but perhaps not by an order of magnitude. An order of magnitude estimate of discharge can be made if we assume a flow depth of 5 m, a velocity of 7 m/sec., and a width needed to span the Niagara Peninsula normal to the mean flow direction of 60 km. The answer is 2.1×10^6 cumecs, a comparable figure to those calculated by Shaw *et al.* (1989).

Little can be said about the temporal characteristics of the flow from the evidence available. However, considerable erosion of rock (up to 3 m) is implied by Figure 4, for example, which apart from a cluster of comparable smaller forms nearby, stands isolated above a limestone pavement surrounded by a very subdued relief. As the general surface lowered the general level at which erosive activity was concentrated may have changed, and it may be misleading therefore to see all forms as strictly synchronous even if the flows where relatively short-lived, as theory suggests (Shaw *et al.*, 1989; Shaw and Gilbert, 1990).

Finally, it may be concluded from the complete lack of a related sedimentary overburden to the fluted surfaces (such as well-rounded sands and gravels), that the flows ceased gradually. A full flow abruptly stopped would surely leave traces of its clastic load. A flow declining gradually might be able to remove loose debris although not longer able to strip new clasts from the bed. Fluvial bedrock channels are usually quite clear of débris after flood events. The alternative is that the clastic load was removed by subsequent glacial entrainment.

THE ALGONQUIN AND ONTARIAN EVENTS

It is worth considering the Niagara Peninsula evidence in the light of the recent hypotheses of Shaw and Gilbert (1990) that the Ontario and Erie basins have been shaped by two subglacial meltwater floods: the Algonquin and the Ontarian events. Our evidence is consistent with the later Ontarian event insofar as the orientation of fluted surfaces is concerned. However, if the extension of the scale range to include large kilometre scale promontories, and their concomitant re-entrants, along the Niagara Escarpment is accepted then some difficulties are posed. Straw (1968) maps the re-entrants and the implied ice-flow direction as far north as Cabot Head. Only in the Beaver Valley and Blue Mountain area is there any sign of a discontinuity in the regional flow direction (towards a more northerly flow). South of Blue Mountain the shaping of the Niagara Escarpment is not consistent with the flow lines of the Algonquin event. Between Cape Croker and Cabot Head the re-entrants seem equally consistent with the orientation of either hypothesised flood event.

Within the Niagara Peninsula there is a complete absence of flow features consistent with the Algonquin event, either in bedrock or in drift. It is not our opinion that the entire sculpting of the Escarpment within the Peninsula can be attributed to a single event, for that leaves unanswered what the form was before, and why it may not have developed in a similar fashion during earlier phases of glaciation. It is harder still to imagine that an entire suite of bedrock landforms comparable in magnitude to the present ones, but oriented according to the Algonquin flow lines, could be completely effaced without trace by the subsequent Ontarian event.

GLACIAL ABRASION

Wherever striae are seen they have an orientation 10 to 15 degrees more northerly than that of the fluted surfaces. We assume that these marks, presumably made by boulders embedded in basal ice, represent the final phase of shaping on the bedrock surface and that the change in direction marks a shift in direction of the regional ice flow.

CONCLUSIONS

The continuous spectrum of forms we have described, the resistance of the dolostones of the lower Lockport Group, and the ubiquity of the features along the Niagara Escarpment leave little doubt that the p-forms described here represent a dynamic adjustment of form, the obstacle presented by the Escarpment, to an erosive process, subglacial meltwater. What we see is what was left when the meltwater ceased to operate, and therefore it need not represent an equilibrium morphology, merely the stage reached. For this reason much of the apparent variety in form may be accounted for by regarding the landforms as a space/time assemblage whose development ceased abruptly when the flow ceased.

All the fluted surfaces we have seen disappear beneath the Vinemount moraine to the south, and glacial striae cross over and through them at a more northerly angle by ten to fifteen degrees. We deduce from the large scale of some of the p-forms seen that they were sculpted by high magnitude subglacial meltwater flows, and that surface scratching by boulders embedded in ice is a later event. Prior to either of these events it seems logical that either glacial action or initial meltwater discharge prepared the surface by removing horizontally bedded units of the Lockport Group which had been dismembered during ice-free periods by karst action, as would be the case now if glacial ice returned.

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REFERENCES

Agassiz, L., 1840. On the polished and striated surfaces of the rocks which form the beds of glaciers in the Alps. Proceedings of the Geological Society of Scotland, London, 3: 321-322.

Allen, J. R. L., 1970. Physical processes in sedimentation. George Allen and Unwin, London, 248 p.

——— 1971. Transverse erosional marks of mud and rock: their physical meaning and geological significance. Sedimentary Geology, 5: 167-385.

——— 1984. Sedimentary Structures, their character and physical basis. Elsevier Scientific Publishing Company, Amsterdam, 663 p.

——— 1985. Principles of physical sedimentology. Allen Unwin, London, 272 p.

Andrews, E., 1883. Glacial markings of unusual forms in the Laurentian Hills. The American Journal of Science, 125: 151-156.

Bernard, C., 1972. Les marques sous-glaciaires d'aspect plastique sur la roche en place (p-forms): interprétation génétique. Revue de géographie de Montréal, 26: 177-191.

Boulton, G. S., 1973. The origin of glacially fluted surfaces — observations and theory. Journal of Glaciology, 17: 287-309.

Brett, C. A. and Calkin, P. E., 1987. Niagara Falls and Gorge, New York-Ontario, p. 97-105. *In* D. C. Roy (ed.), Geological Society of America Centennial Field Guide — Northeastern Section. Volume 5, 481 p.

Chamberlin, T. C., 1888. The Rock-scorings of the Great Ice Invasions, p. 155-248. *In* J. W. Powell (Director), 7th Annual Field Report 1885-6. United States Geological Survey, 656 p.

Dahl, R., 1965. Plastically sculptured detail forms on rock surfaces in northern Nordland, Norway. Geografiska Annaler, 47A(2): 83-140.

Dionne, J.-C., 1987. Tadpole rock (rocdrumlin): a glacial streamline moulded form, p. 149-159. *In* J. Menzies and J. Rose (eds). Drumlin Symposium. Balkema, Rotterdam.

Edelman, N., 1949. Some morphological details of the roches moutonnées in the archipelago of S. W. Finland. Bulletin de la Commission géologique de la Finlande, 144: 129-137.

——— 1951. Glacial abrasion and ice movement in the area of Rosala-Nötö, S. W. Finland. Bulletin de la Commission géologique de la Finlande, 154: 157-169.

Feenstra, B. H., 1981. Quaternary Geology of the Niagara/Welland Area. Ontario Geological Survey, Open file Report 5361.

——— 1986. Niagara/Welland — Quaternary Geology. Ontario Geological Survey, Map 2496.

Flint, J. J. and Lolcama, J., 1985. Buried Ancestral drainage between Lakes Erie and Ontario. Geological Society of America Bulletin, 97: 75-84.

Gjessing, J., 1965. On 'plastic scouring' and 'subglacial erosion'. Norsk Geografisk Tiddskrift, 20: 1-37.

Hall, J., 1815. On the Revolutions of the Earth's surface. Royal Society of Edinburgh Transactions, 8: 139-67, 169-212. (Note that the following reference is by a different J. Hall.)

Hall, J., 1843. Geology of New York. Part IV. Comprising the Survey of the Fourth Geological District, State of New York, Albany, 685 p.

Hjulström, F., 1935. Morphological activity of rivers as illustrated by the river Fyris. Bulletin of the Geological Institute of the University of Uppsala, 25: 221-527.

Huggett, R. J., 1989. Superwaves and superfloods: The bombardment hypothesis and Geomorphology. Earth Surface Processes and Landforms, 14: 433-442.

Ljungner, E., 1930. Spaltentektonik und morphologie der schwedischen Skagerrak-Küste. Bulletin of the Geological Institute of Uppsala, 21: 1-478.

Lyell, C., 1845. Travels in North America (2 volumes). John Murray, London, 316 p. and 272 p.

Maxson, J. H. and Campbell, I., 1935. Stream fluting and stream erosion. Journal of Geology, 43: 729-744.

Pluhar, A. and Ford, D. C., 1970. Dolomite Karren of the Niagara Escarpment, Ontario, Canada. Zeitschrift für Geomorphologie, 14: 392-410.

Prest, V. K., 1983. Canada's Heritage of Glacial Features. Geological Survey of Canada Miscellaneous Report 28, 119 p.

Sharpe, D. R. and Shaw, J., 1989. Erosion of bedrock by subglacial meltwater, Cantley, Quebec. Geological Society of America Bulletin, 101: 1011-1020.

Shaw, J., 1988. Subglacial erosion marks, Wilton Creek, Ontario. Canadian Journal of Earth Sciences, 25: 1256-1267.

Shaw, J. and Gilbert, R., 1990. Evidence for large-scale subglacial meltwater flood events in southern Ontario and northern New York State. Geology, 18: 1169-72.

Shaw, J., Kvill, D. and Rains, B., 1989. Drumlins and catastrophic subglacial floods. Sedimentary Geology, 62: 177-202.

Shaw, J. and Sharpe, D. R., 1987a. Drumlins and Erosion Marks in Southern Ontario. Excursion Guide Book C-25, INQUA XII International Congress, Ottawa, 17 p.

——— 1987b. Drumlin formation by subglacial meltwater erosion. Canadian Journal of Earth Sciences, 24: 2316-2322.

Straw, A., 1968. Late Pleistocene glacial erosion along the Niagara Escarpment of Southern Ontario. Geological Society of America Bulletin, 79: 885-910.

Wright, G. F., 1889. The Ice Age in North America and its bearing on the antiquity of man. D. G. Appleton, New York, 622 p.