Erosion of bedrock by subglacial meltwater, Georgian Bay, Ontario: a regional view[1]

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A spectacular series of sculpted erosional forms (s-forms) is mapped and described from a 70 km wide area along the shore of Georgian Bay, Ontario, which, except for a scattered boulder lag, has been swept clean of sediment. A great variety of sculpted forms is described and illustrated and grouped into three classes: transverse, longitudinal, and nondirectional forms. Transverse forms comprise transverse troughs, muschelbrüche, sichelwannen, and comma forms; longitudinal forms comprise spindle flutes, cavettos, and furrows; and nondirectional forms consist of undulating surfaces and potholes. Transverse forms are preferentially located on stoss slopes, and longitudinal forms on lee slopes of rock rises. Undulating, nondirectional forms are found on distal slopes, and potholes at major breaks in slope. This correlation of form and bed topography suggests that relief exerts considerable control on both form and location. Form geometry is also inferred to be related to coherent flow structures and their interaction with the bed. Flow scale, vorticity, separation, bifurcation, strength, and direction are inferred from erosional-mark properties. In some cases, erosional forms appear to have caused the flow structure by which they were perpetuated. Sculpted forms occur at different scales, and the inferred flow structures are thought to have operated over the same scale range.

Attributes of the forms, boulder lags, and inferred flow structures clearly reflect erosion by powerful, turbulent, subglacial meltwater flows. The erosional forms are observed over an area 70 km wide, which, taken together with a strongly uniform paleoflow direction, indicates regional-scale flow. The Georgian Bay floods were comparable in discharge ($\sim 10^7$ m^3/s) with floods from glacial Lake Missoula, Livingstone Lake drumlins, and Sable Island tunnel valleys. The most likely site for the storage of meltwater that drained catastrophically to form the erosional-mark field was the lowland stretching north from the Abitibi Highlands to Hudson Bay.

Une série de formes spectaculaires, sculptées par l'érosion (formes-s), a été cartographiée et décrite dans une bande de terrains d'une largeur de 70 km, qui longe la rive de la baie Georgienne, en Ontario, et à part l'existence de blocs dispersés, ces formes furent nettoyées de sédiment par l'action érosive. Un grand nombre des ces formes sculptées, variées, ont été décrites, illustrées et regroupées dans les trois classes suivantes : formes tranversales, longitudinales et sans direction privilégiée. Les formes transversales sont représentées par des fossés, muschelbrüche, sichelwannen et figures de virgule; les formes longitudinales comprennent des rainures en aiguille, cavettos et sillons; et les formes sans direction privilégiée incluent des surfaces onduléés et des marmites. Les formes transversales sont plus fréquentes sur les pentes amont et les formes longitudinales sur les pentes aval des rochers en saillie. Les formes ondulantes, qui n'exhibent pas de direction privilégiée, sont observées sur les pentes distales, et les marmites apparaissent dans les zones de changement brusque de pente. Cette corrélation des formes avec la topographie des couches sédimentaires impute au relief une influence considérable dans le développement des formes et leur localisation. La géométrie des formes est apparemment reliée aux structures d'écoulement cohérentes et à leur interaction avec les couches sédimentaires. La vitesse d'écoulement, la vorticité, la séparation, la force et la direction sont déduites des propriétés des figures d'érosion. Dans certains cas, il semble que les formes d'érosion aient déterminé la structure d'écoulement, qui a joué un rôle majeur dans la préservation de ces formes. Les formes sculptées sont observées à differentes échelles, et les structures d'écoulement présumées semblent avoir agi à une échelle de même ordre de grandeur.

Les particularités des formes, les traînées de blocs, et les structures d'écoulement présumées reflètent clairement une action érosive produite par des courants sous-glaciaires turbulents et puissants. Les formes d'érosion, observées dans une aire de 70 km de large, et la direction largement uniforme des paléo-écoulements, indiquent un écoulement à l'échelle régionale. Les flots dans la baie Georgienne étaient comparables en débit ($\sim 10^7$m^3/s) aux flots associés au lac glaciaire de Missoula, aux drumlins du lac Livingstone et aux ravins sous-glaciaires de l'île Sable. Le site du réservoir d'accumulation des eaux de fonte des glaces, dont le drainage violent a engendré les phénomènes d'érosion, serait vraisemblablement la région basse située au nord, allant des hautes-terres d'Abitibi jusqu'à la baie d'Hudson.

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Introduction

We describe and classify erosional marks in bedrock from around the northeastern shores of Georgian Bay and interpret them as products of vast subglacial meltwater floods. Our aims are to understand how erosional marks are formed and to use them to learn about catastrophic flooding beneath the Laurentide Ice Sheet. We concentrated our study along the shoreline itself, where erosional marks are well preserved.

We pay particular attention to the question of whether erosion was mainly by glacier ice or meltwater. This is most debatable for large-scale forms whose terminology (e.g., glacial groove, glacial fluting, and ice-molded rock drumlin) is commonly suggestive of glacial processes. But small-scale erosional marks, which are interpreted as meltwater forms, are either morpholo-

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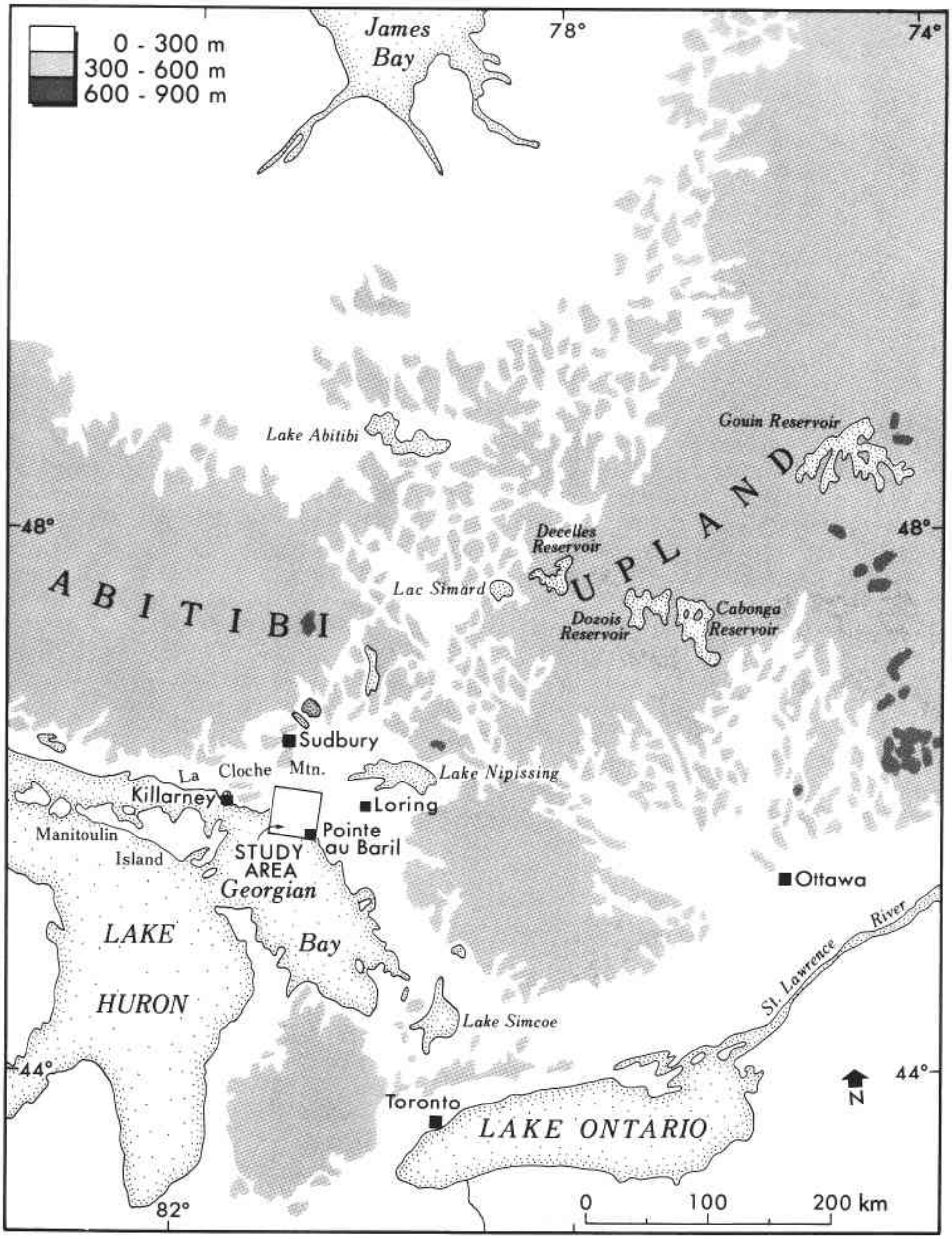

FIG. 1. Location map showing general topography. Note the anastomosing pattern of uplands between the study area on Georgian Bay and the James Bay Lowlands. Modified from Geological Survey of Canada Map 1399A (Geological Survey of Canada 1976).

gically similar to larger scale forms or intimately related to them, and our classification is virtually independent of scale. The inevitable conclusion is that s-forms are produced by meltwater.

We mapped the distribution and alignment of large-scale forms from aerial photographs and explain them by erosion by a broad, subglacial flood. Subglacial meltwater discharge estimates of about $10^7\,m^3/s$ are based on this mapping and on some simple assumptions on the relationships between local topography and flow depth and the size of clasts resting on the erosional surface and flow velocity.

Study area

Location and physiography

We studied sculpted erosion forms on extensive bedrock exposures along the northeastern shore of Georgian Bay, Lake Huron (Fig. 1). The s-forms are cut into an ancient eroded surface of crystalline bedrock, the Georgian Bay Fringe of Chapman and Putnam (1984), characterized by low relief, very shallow, discontinuous soils, and bare rock plains, knolls, and ridges. The study area is confined by bedrock uplands to the west, north, and east and is situated south of a broad saddle in the Abitibi Upland that is dissected by an anastomosing valley system (Fig. 1). The minimum regional range of the erosional features extends eastward from Manitoulin Island through the La Cloche Mountains, to the south as far as Pointe au Baril, northward possibly as far as Sudbury, and as far east as Loring (Fig. 1). The erosional forms are particularly well developed on the barren rocky plains along a 70 km stretch of Georgian Bay shoreline between Killarney and Pointe au Baril.

Bedrock geology

The study area straddles the Grenville Front, a wide, northeast-trending structural zone of metamorphic rocks separating the Superior Province to the north from the Grenville Province to the south. This structural zone consists of narrow bands of northeast-striking lenticular orthogneiss, layered gneiss, migmatite, and intervening mylonite, all dipping moderately southeast (Davidson and Bethune 1988). These rocks are predominantly coarse grained. South of the Grenville Front, bedrock of the Britt Domain, a southeasterly trending structural element within the Grenville Province, consists of strongly metamorphosed, coarse-grained granitic rock.

General late Quaternary history

Striae and chattermarks indicate that ice flowed from northeast to southwest across the area (Chapman and Putnam 1984; Kor and Delorme 1989). Fine striae are pervasive on most bedrock surfaces, including the surfaces of most sculpted erosional forms.

The Late Wisconsinan deglaciation of Georgian Bay, from roughly 11 000 to 10 000 BP, was accompanied by the expansion of glacial Lake Algonquin, a large ice-contact lake forming part of the late glacial Great Lakes system (Karrow *et al.* 1975; Lewis and Anderson 1989). Ice retreat left few recessional features representing former ice margins in the area (Kor, in press).

Subglacial meltwater flow, as recorded by small, subaquatic outwash fans throughout the low terrain east of Georgian Bay (Delorme 1989; Kor, in press), played a significant role in this deglaciation. Extensive glaciofluvial deposits along the base of the Algonquin Highlands northward to the Harricana Moraine suggest that subglacial meltwaters may have been concentrated in a narrow zone in the retreating glacier (Veillette 1986). The strongly sculptured bedrock surface in the study area and tunnel valleys at the south end of the Georgian Bay basin (Barnett 1990) also indicate the action of subglacial meltwater during deglaciation.

Wave action in postglacial lakes, primarily of the glacial Lake Algonquin (12 400 – 11 400 BP) and post-Algonquin lake phases (about 11 400 – 10 200 BP) and the Nipissing Great Lakes (about 5500 – 4000 BP), reworked or removed some surficial sediment, but the erosion was mainly by subglacial meltwater floods.

Previous work

There is an extensive literature on sculpted bedrock features, so-called p-forms, and we refer readers to benchmark papers by Ljungner (1930) and Dahl (1965) for a historical perspective. Bernard (1971) complements these papers by reviewing the modern literature and adding to the catalogue of erosional marks.

Ljungner (1930) was the first scientist to pay serious attention to these erosional forms. He argued strongly in favour of a meltwater origin for erosional marks in Sweden. Others used detailed morphological descriptions, experiments reproducing erosional marks, and analogies with bedforms created by turbulent flows to support this conclusion (Dahl 1965; Allen 1984; Shaw and Kvill 1984; Shaw 1988*a*; Sharpe and Shaw 1989; Shaw *et al.* 1989). In view of such strong support for a meltwater origin, we suggest that the term p-form, which implies formation by a plastic rather than a turbulent viscous medium (Dahl 1965), should be replaced with the more general term *s-form*, standing for *sculpted form*.

Ljungner (1930) and Dahl (1965) described individual forms in detail, made observations on the relationships between forms and their patterns, and carried out critical analysis of how the spatial distribution of forms related to topography. Although Ljungner (1930) stressed the importance of topography on the location of forms, he concluded that they owed their origins primarily to traces of turbulent flow arising in subglacial meltwater. Similarly, Johnsson (1956), who favoured an improbable fluid medium, argued that differences in frequency relate to differences in flow characteristics.

Allen (1971) opened the modern era of erosional-form study with a careful description of experimental forms and their evolution over time. He emphasized flow structure and its influence on bed shear stress during the formation of erosional marks and reconstructed skin friction lines to show the relationship between form and flow separation. He concluded that vortices and rollers, which are cell-like rotating structures in the flow, strongly influence the erosion patterns.

Allen (1971, 1984) then argued that flow separation, which is fundamental to the formation of erosional marks, is directly related to defects or irregularities on the bed. But Curl (1966) and Blumberg and Curl (1974) noted that flows producing solutional erosional marks maintain a constant form Reynolds number (the ratio of inertial to viscous forces, with flute length as the characteristic length). In Allen's view, the form Reynolds number varies with time, and he presents experimental confirmation of this (Allen 1971).

Allen (1971, p. 334) did, however, acknowledge that his defect approach loses its validity when, after a certain time, primary marks give rise to secondary and tertiary marks; vortices shed by primary marks give birth to new marks. He concluded that erosional marks reflect the duration of the flow and an interaction between flow dynamics and obstacles or inhomogeneities on the bed.

We apply Allen's general conclusions in an explanation of s-forms on bedrock along the northeastern shores of Georgian Bay and show that the types of erosional marks and their assemblages are closely tied to local relief, a result stressed by others (Ljungner 1930; Dahl 1965; Bernard 1971; Gray 1981; Murray and Shaw 1988; Sharpe and Shaw 1989).

In subglacial meltwater flows there is no shortage of vortices. Horseshoe vortices are generated at bluff obstacles such as large boulders on the bed or projecting from the ice, and Taylor vortices are formed where fast-flowing inner fluid is accelerated outwards at bed concavities and displaces slower fluid near the bed. Many forms were probably not initiated by adjacent defects but by impingement on the bed of such vortices generated upflow (Shaw 1988*a*), or by the instability of these vortices near the bed (Allen 1971, Fig. 7). Thus, our deduction that muschelbrüche, formed without evident flow separation, evolved to sichelwannen implies that in Allen's view neither of these forms is primary.

We imagine fields of erosional marks are formed by families of longitudinal, counter-rotating vortices. As s-forms mature and cause flow separation, the vortices they shed give birth to new forms which also shed vortices. Thus, there are families of s-forms and a tendency to "space filling" as the bed is progressively covered by erosional marks.

The scale of the flow clearly determines the maximum scale of coherent flow structures generating erosional marks, but few authors have considered the overall scale of flows generating such marks. Dahl (1965) suggested flows of limited extent on the evidence that s-forms occur in patches. He reasoned that this was because the flows were partially englacial and partially subglacial. However, we suspect that he underestimated their spatial extent because he failed to recognize that much rounded and faceted exposed rock, although not carrying obvious s-forms, may well be a product of subglacial meltwater sculpting.

In addition, the extent of subglacial meltwater flows might be underestimated because s-forms are not well preserved on rock exposed to weathering for a long time; they are best preserved on bedrock surfaces recently raised above lake or sea level or exhumed from beneath a sediment cover.

Some fields of s-forms resulted from regionally extensive flows (Shaw and Sharpe 1987; Murray and Shaw 1988; Shaw 1988*b*; Gilbert 1990). We support this conclusion and discuss s-forms here at site and subsite, local and regional scales. Although there are distinctive elements at each scale, it is remarkable how well they fit together. This systematic organization of the Georgian Bay erosional marks is seen on large- and small-scale maps and photographs and is the basis for our conclusions on the hierarchical nature of s-forms. It speaks also for a subglacial meltwater flood towards the southwest at least 70 km across.

Definition and classification of s-forms

Bedforms sculpted by fluvial action are widely described in the literature, but there has been no attempt at a systematic classification with specific definitions. The number of recognized forms has increased recently, and it is timely to take stock and to define the descriptive terms attached to the various s-forms. This classification may be expanded as more forms are described.

Erosional marks are first classified here according to their orientation with respect to flow direction: transverse, longitudinal (flow parallel), and nondirectional. The main distinguishing form element is the plan shape of the enclosing rim. Forms are further subdivided on the basis of their internal morphology. Finally, in some cases, the position of the form on the local topography is also used in the classification. The classification is almost independent of scale.

This s-form classification is presented below, and each form is illustrated diagramatically and photographically (Figs. 2, 3). We cite the earliest or a particularly significant work referring to each form, although since we describe the geometry of forms with a modern understanding of formative processes in mind, our definition may differ slightly from the original.

Transverse s-forms

Muschelbrüche (singular muschelbruch)

Muschelbrüche are mussel-shell-shaped, shallow depressions with sharp, convex upflow rims and indistinct, downflow margins merging imperceptibly with the adjacent rock surface (Figs. 2*a*, 3*a*) (Ljungner 1930). Although both are gentle, the proximal slope is normally steeper than the distal slope, otherwise, there are no distinguishing internal form elements.

Sichelwannen (singular sichelwanne)

Sichelwannen are sickle-shaped marks (Figs. 2*b*, 3*b*) (Ljungner 1930) resembling the classical transverse erosional marks of Allen (1971, Fig. 1). They have sharp rims (r) convex-up flow, and a crescentic main furrow (mf), extending downflow into arms wrapped around a median ridge (mr). Lateral furrows (lf) may flank the main furrow.

Comma forms

Comma forms are similar to sichelwannen but with only one arm well developed; the other arm is either missing or poorly formed (Figs. 2*c*, 3*c*) (Shaw and Kvill 1984). Comma forms are part of a continuum with sichelwanne and may be considered transitional between transverse and longitudinal forms.

Transverse troughs

Transverse troughs are relatively straight troughs arranged perpendicular to flow, with lengths much greater than widths (Figs. 2*d*, 3*d*). They commonly have a steep, relatively planar upflow slope or lee face (lf) below a relatively straight rim (r). The downflow or riser slope (rs) is gentler and normally eroded by shallow, stoss-side furrows (ssf), which produce a sinuous slope contour. Large transverse troughs are normally compound forms enclosing numerous, smaller scale s-forms.

Longitudinal s-forms

Spindle flutes

Spindle flutes are narrow, shallow, spindle-shaped marks much longer than they are wide and with sharp rims bounding the upflow side (Figs. 2*e*, 3*e*) (Allen 1971). They are pointed in the upflow direction and broaden downflow. Whereas *open* spindle flutes merge indistinctly downflow with the adjacent surface, *closed* spindles have sharp rims closing at both the upflow and downflow ends. Spindle flutes may be asymmetrical, with one rim more curved than the other.

Cavettos

Cavettos are curvilinear, undercut channels eroded into steep, commonly vertical or near-vertical rock faces (Figs. 2*f*, 3*f*) (Johnsson 1956). The upper lip is usually sharper than the lower one, although both may be sharp.

Stoss-side furrows

Stoss-side furrows are shallow, linear depressions on the stoss side of bedrock rises, giving a regular, gently curving, sinuous contour to the slope (Figs. 2*d*, 3*d*).They have rounded rims and are open at both ends.

Furrows

Furrows are linear troughs, much longer than wide, that carry a variety of s-forms and remnant ridges on their beds and walls (Figs. 2*g*, 3*g*). Rims are remarkably straight when viewed over the full length of furrows but are usually sinuous in detail, commonly regularly so, as a result of sculpting into the trough walls by smaller, included s-forms.

Nondirectional s-forms

Undulating surfaces

Undulating surfaces are smooth, nondirectional, low-amplitude undulations found on gentle lee slopes of rock rises (Figs. 2*h*, 3*h*).

Potholes

Potholes are near-circular, deep depressions that may show spiralling, rising flow elements inscribed on their walls (Figs. 2*i*, 3*i*) (Gilbert 1906; Alexander 1932).

This classification emphasizes the negative erosional forms that represent zones of high relative erosional rates. But distinctive positive forms also result from this differential erosion. The median ridges of sichelwannen and residual ridges between diverging furrows are "streamlined," with a broad, rounded upstream portion and a tapered tail. These are defined as "rock drumlins" and belong to the class of erosional drumlins (Shaw and Sharpe 1987).

Smaller scale s-forms are sculpted into the surfaces of the rock drumlins (Fig. 4). This is best developed on the upstream and flanking faces where transverse s-forms are prevalent. Longitudinal forms are more common on the gently sloping distal portions of rock drumlins, although cavettos are found on some steep flanks.

Introductory discussion on genesis

We mentioned in the introduction that s-forms are eroded by coherent flow structures (vortices) or assemblages of flow

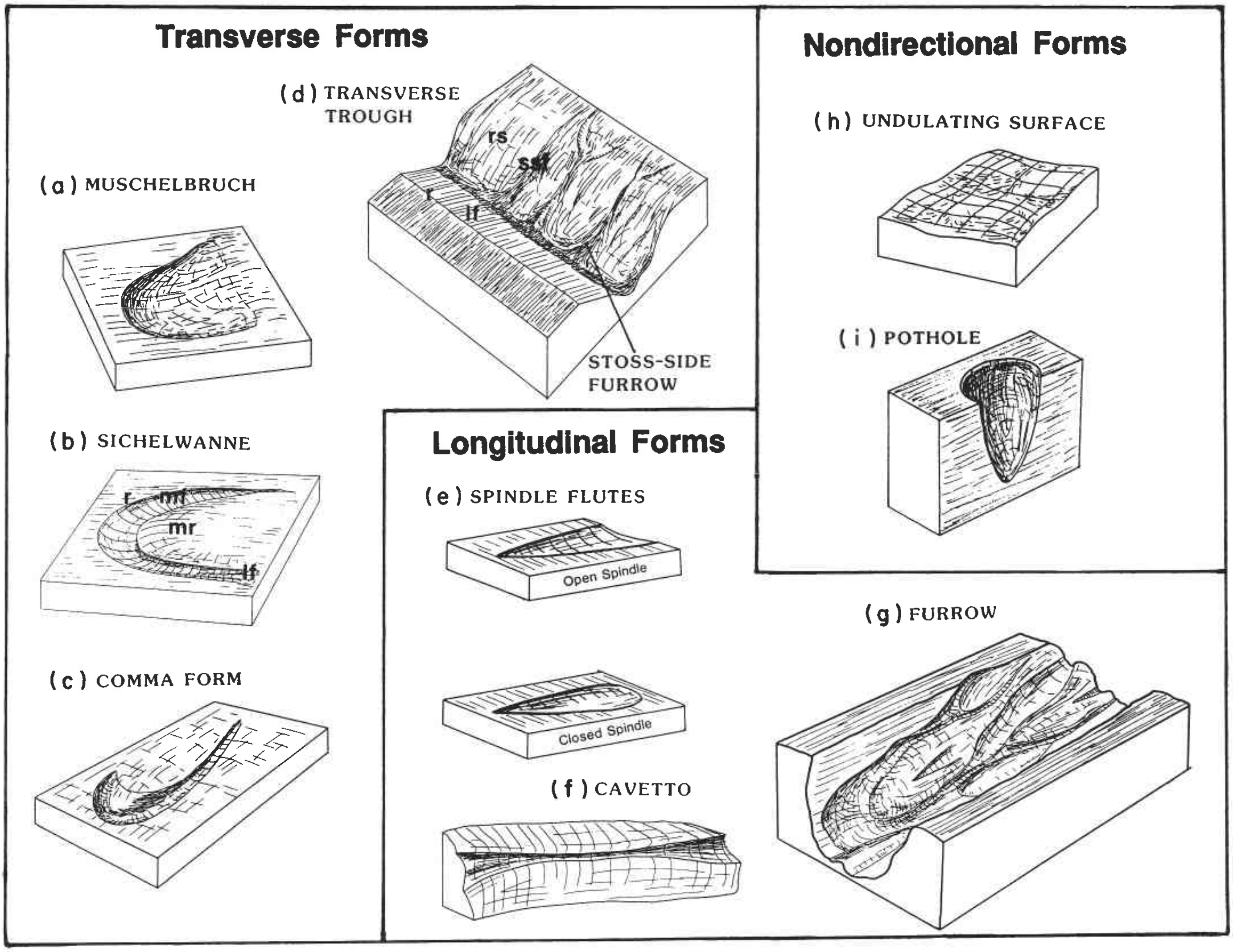

FIG. 2. Atlas of s-forms identified and sketched from the French River complex. Flow direction from left to right in all but nondirectional forms. See text for definitions.

structures. This is illustrated for the case of muschelbrüche evolving into sichelwannen (Fig. 5).

Some muschelbrüche are so subtle that they scarcely represent more than a parabolic area of polished rock surface. With continued abrasion, a shallow depression evolves, but the angle between the surrounding bed and the proximal slope of the s-form is extremely small, much less than the 4° necessary to cause flow separation (Allen 1984, p. 113). Consequently, separated flow cannot explain the formation of muschelbrüche, and we argue that they result from the impingement on the bed of a vortex or other coherent flow structure (Fig. 5*b*). A similar explanation is given for spindle forms, but with a lower angle of attack for the impinging vortex (Fig. 5*a*) (Shaw 1988*a*).

As a muschelbruch deepens, its proximal slope steepens and, at some point, flow separation occurs, like that in classical flutes (Fig. 5*c*) (Allen 1984). The secondary flow actually created by the bed form then controls the erosional process, and the form becomes self-perpetuating. The classical sichelwanne results.

Allen (1971) presented behavioural evidence supporting these conclusions on the formation of sichelwannen, muschelbrüche, and spindle flutes. He observed that erosional marks of the sichelwanne type grow larger with time, but spindle forms may grow and then become smaller as the bed around them erodes faster than they do. This makes sense if sichelwannen are self-perpetuating, but flutes depend on vortices that are independent of the form and may be short-lived.

French River s-form complex

Sculptured bedrock forms in the French River area were previously noted and described by Andrews (1883), Quirke and Collins (1930), and McKenzie (1979). These workers were evidently unaware of the vast regional extent of the complex of s-forms, which became apparent only with systematic study of airphotos. Kor and Delorme (1989) recognized a large portion of the French River s-form complex while mapping landforms and surficial deposits. We travelled by helicopter and boat to map the area covered by bedrock erosional marks (Fig. 6).

We describe sculpted bedrock forms from eight sites near the mouth of the French River, from Philip Edward Island to Henvey Inlet (Fig. 6). We measured the length, width, depth, and axial direction of all forms encountered within a delineated area at seven of these sites. We also noted the size, roundness, and location of erratic boulders stranded on the bedrock surface. We noted the presence of glacial erosional forms, primarily striae and chattermarks, and measured their orientations. We also recorded bedrock lithology, structure (fracture patterns), and local topography.

Subglacial meltwater erosional forms in the French River area

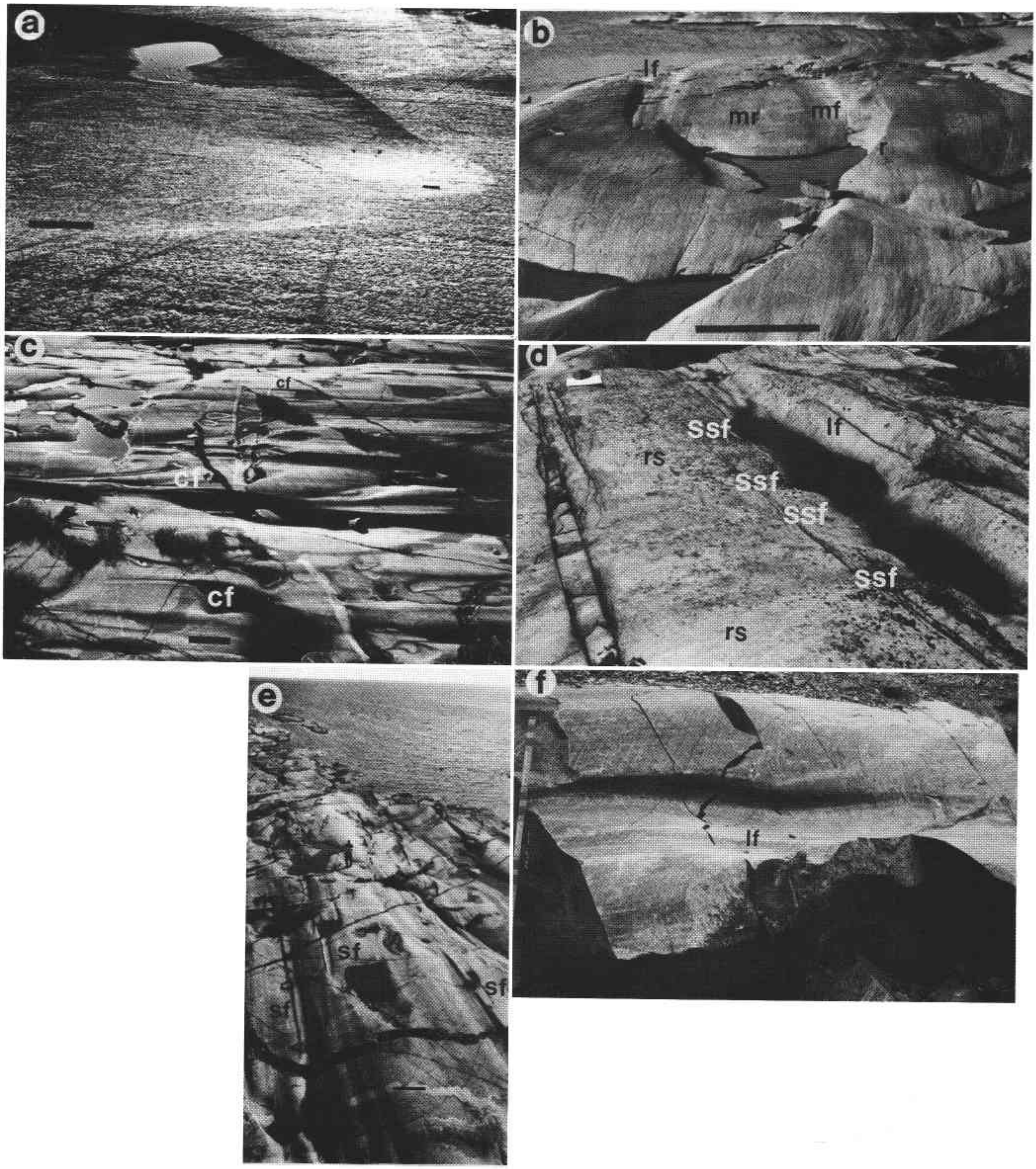

FIG. 3. Atlas of photographs of s-forms and their associations. (*a*) Muschelbruch. Note the high polish within and rougher surface and heavier striation outside the form. Flow right to left. Scale bar = 50 cm. (*b*) Sichelwanne with sharp rim (r), main furrow (mf), lateral furrow (lf), and median ridge (mr). Flow away from viewer. Scale bar = 1 m. (*c*) Comma forms (cf) with differing degrees of elongation. Flow right to left. Scale bar = 2 m. (*d*) Transverse trough. Note the steep, planar lee face (lf) and the riser slope (rs) with sinuous contour. Stoss-side furrows (ssf) and incipient sichelwannen are accented by water. Note that the trough was not formed along the strongest joints in the vicinity. Flow right to left. White tile is 31 × 31 cm. (*e*) Spindle flutes (sf) with varying degrees of splaying. Note all are of the open type. Flow away from viewer. Scale bar = 2 m. (*f*) Cavetto cut into a rock wall. The upper lip (shaded) overhangs. Note the small lateral furrow (lf) below the lower lip. The form broadens downflow, that is, right to left. Metre stick for scale.

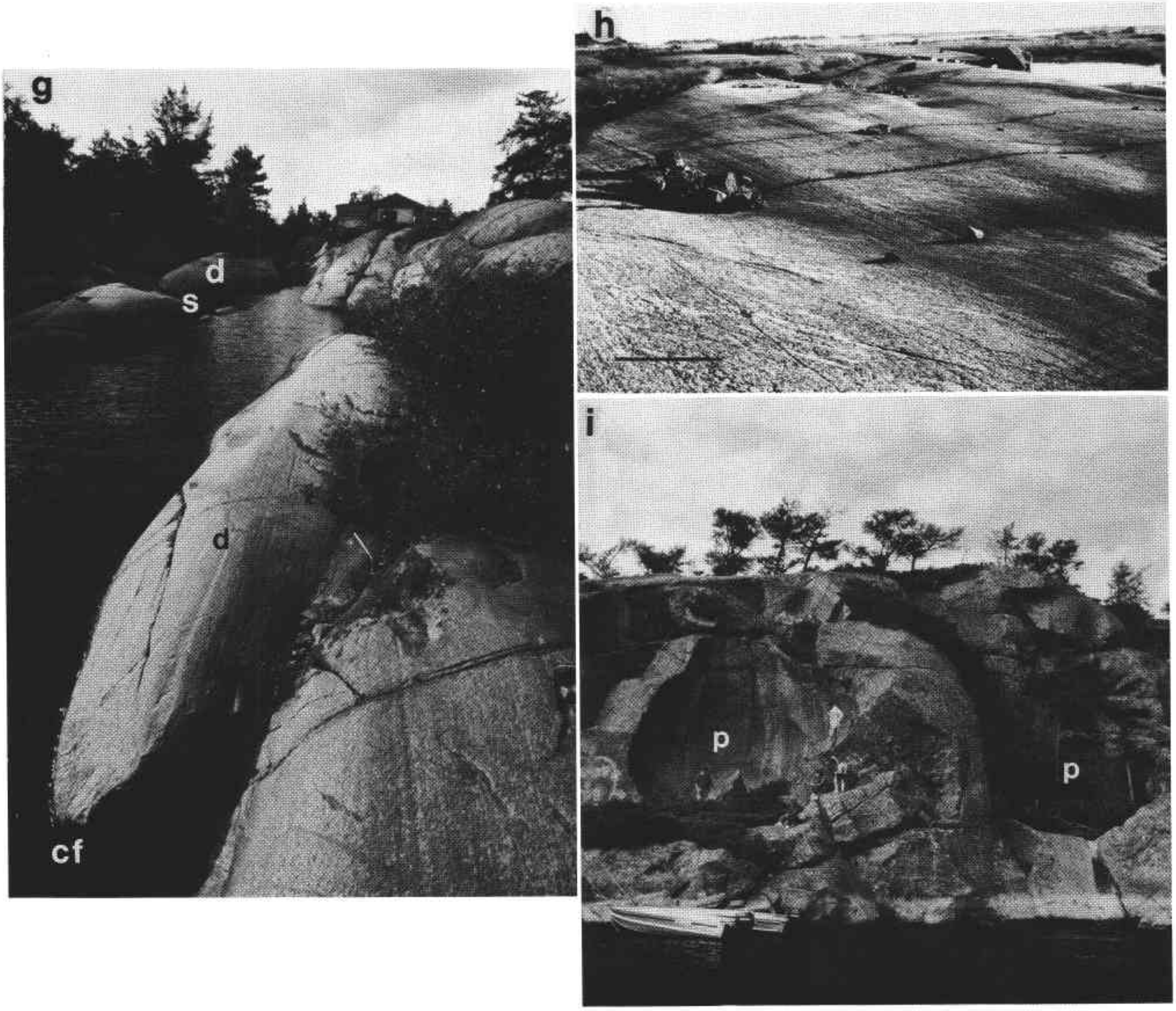

FIG. 3 (*concluded*). (*g*) Furrow. Linear trough composed of sichelwannen (s) and comma forms (cf) separating rock drumlins (d). Flow away from viewer. Old cabin for scale. (*h*) Undulating surface. Note the absence of other s-forms. Flow from lower right. Scale bar = 1 m. (*i*) Potholes. Two potholes (p) on the lee slope of a major topographic break in a region dominated by large-scale furrows. Flow towards the viewer. Note that the distal walls (closest to the viewer) of the potholes have been removed by erosion. Aluminum boats (4 m) for scale.

are arranged in a hierarchy in which small forms are nested within similar, larger forms. Individual s-forms range in size from a few millimetres to several metres, occasionally attaining lengths of hundreds of metres. These are superimposed on linear features up to tens of kilometres long.

Assemblages of individual, small-scale erosional forms are closely related to the morphology of larger relief features. In general, we found short, strongly curved forms such as sichelwannen and comma forms on the steep stoss slopes of rock rises and rock drumlins. Long, relatively straight forms such as furrows and spindles are found on the gentle lee slopes of rock rises and drumlins (Fig. 4).

We discuss the French River erosional marks in categories determined by the side length of the area over which they were studied: (*i*) site (10–100 m) and subsite (metres); (*ii*) local (100–1000 m); and (*iii*) regional (1–10 km).

Site-scale forms (10–100 m)

Detailed analysis of erosional marks has not commonly been carried out, and much remains to be done regarding the relationships between erosional marks and local relief. Ljungner (1930) presented some intriguing insights into this question and, in particular, recorded the tendency for sichelwannen to occur preferentially on the stoss side of bedrock rises on the island of Hålö, Sweden. This same tendency is discussed in more detail for the site scale and reported for the local scale. Similarly, Dahl (1965, Fig. 23) mapped preferential development of sichelwannen on the stoss side of a broad ridge oriented transverse to flow. He also noted the tendency for sichelwannen to be symmetrical where the rock slope was orthogonal to flow and strongly asymmetrical where the flow was along the flanks of a bedrock high. Murray and Shaw (1988) observed this relationship between bedslope, flow direction, and symmetry for erosional marks produced experimentally by dissolution of plaster of Paris by turbulent water flow. These observations on the relationship between form and relief have implications for the genesis of erosional marks and assume importance in the following discussion.

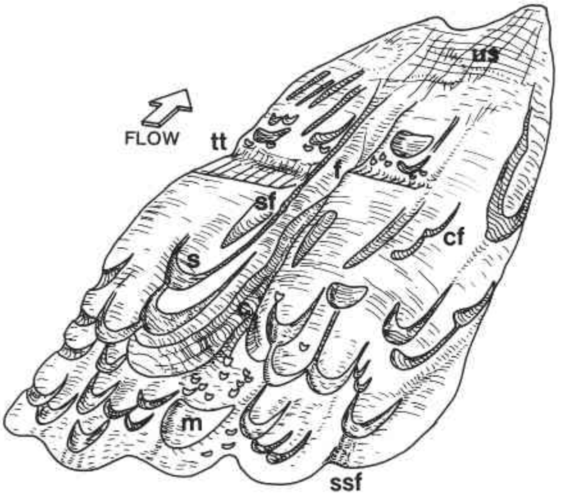

FIG. 4. Idealized sketch of s-forms distributed on rock drumlins. Flow away from the viewer. Abbreviations: tt, transverse trough; s, sichelwanne; m, muschelbruch; ssf, stoss-side furrow; cf, comma form; us, undulating surface; c, cavetto; f, furrow; sf, spindle flute.

The study sites represent the main characteristics of relief and form in the study area. Although there are similarities between each of the sites, detailed associations illustrate distinctive characteristics.

Site A (NTS 41 H/14; UTM 751904)

Site A lies on the northeast flank of a low bedrock island with pronounced sichelwannen in the upflow section. The bedrock is pink migmatite with a well-developed joint set oriented at 145°. The major elements of the surface relief are a series of asymmetrical waves with crests transverse to flow, amplitudes about 2 m, and wavelengths about 15 m (Fig. 7). There are also smaller, superimposed undulations of the bedrock surface. Wave troughs generally correspond to joint sets in the bedrock, suggesting preferential erosion along zones of weakness. However, not all joints are excavated, and wave forms frequently are found between joint sets (Fig. 7).

The most striking feature at site A is the transverse trough (tt) cutting across the middle of the site. Its floor is intensely sculpted with a large number of sichelwannen, indicating flow at right angles to the trough, which are short (1.2–3.0 m) compared with those in adjacent areas. The sichelwannen are short because their close streamwise spacing inhibited the full downstream development of their furrows. Such "interference" is common in areas heavily sculpted by sichelwannen, and the resulting relief is discussed later in some detail. Shallow muschelbrüche (0.04–0.13 m deep) are found together with the sichelwannen, but are less numerous.

The upstream slope of the transverse trough is marked by the lee face (lf, Fig. 7). Its surface is remarkably rectilinear in profile and slopes downstream at about 20°. In this landscape of curvilinear erosional forms, the lee face stands out because it is so planar; its flat surface is cut by only the most weakly defined linear grooves.

Downstream from the trough the surface rises in a convex slope, the riser slope (rs, Fig. 7), sculpted by a series of large-scale sichelwannen (1.30–4.70 m long). Several flow-parallel, shallow furrows (ssf, Fig. 7) extend from the transverse trough, giving the base of the riser slope a sinuous appearance. The furrows have a fairly regular spacing of about 3.5 m and contain small-scale sichelwannen. After ascending the steepest part of the riser slope, these furrows commonly bifurcate to become the main furrows of large-scale sichelwannen that coalesce to form broad basins in the rock surface (Fig. 7). Longitudinal forms, both spindle flutes and the arms of sichelwannen (sf, s, Fig. 7), are prominent on the riser slope. The horns of the farthest downstream sichelwannen extend well down the distal slope.

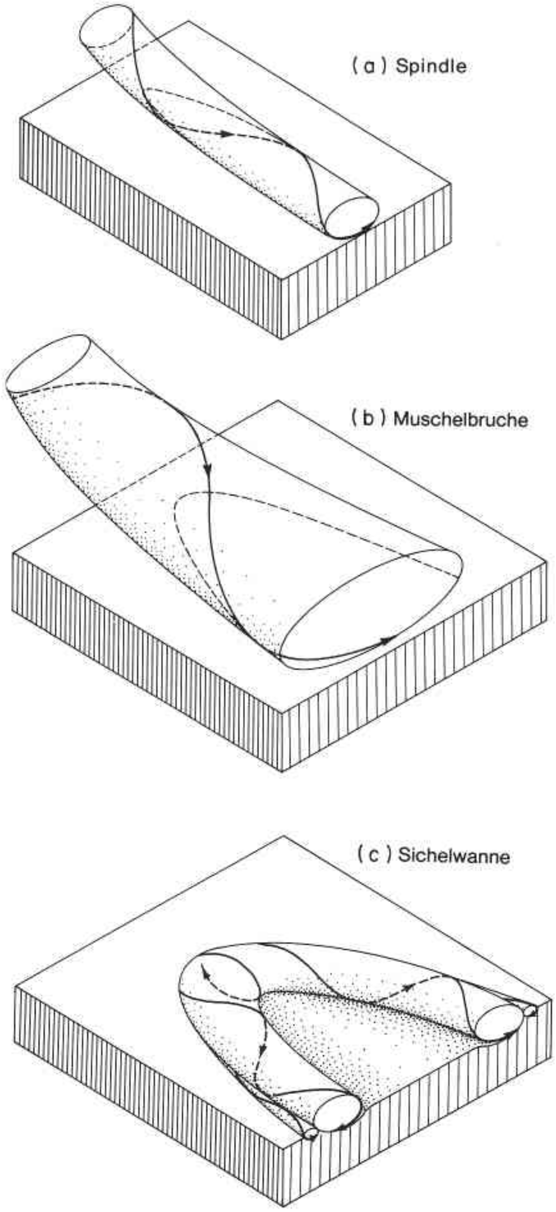

FIG. 5. Inferred relationship between form and flow structure spindle flutes, muschelbrüche, and sichelwannen. (*a*) Spindle flutes form as the result of low-angle vortex impingement causing long, shallow erosional marks. (*b*) Muschelbrüche are formed by higher angle vortex impingement causing flow to spread on contact, resulting in broad, shallow erosional marks. (*c*) Sichelwannen are formed when flow separation beyond the rim produces a roller eddy and vortices that are tied to the bedform and enhance the relief.

The distal slope (ds, Fig. 7), so-called because it is the form element farthest downstream from the transverse trough, is gentle (sloping downstream about 5°) and contains broad, three-

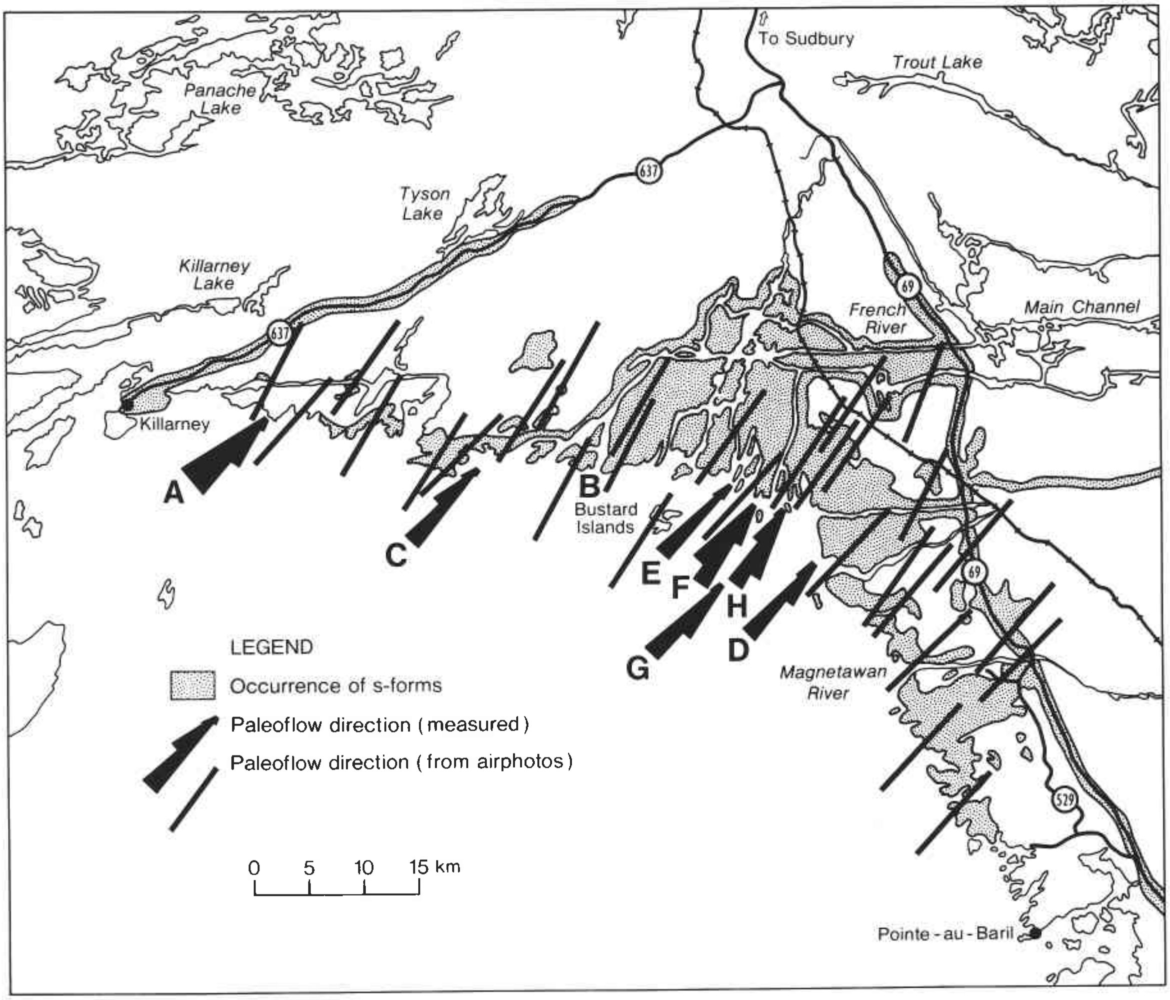

FIG. 6. Study area, northeast section of Georgian Bay, showing observed distribution and orientation of s-forms. Rose diagrams have mean directions and number of observations as follows: site A: $n = 20$, mean = 223°; site C: $n = 17$, mean = 228°; site D: $n = 22$, mean = 223°; site E: $n = 30$, mean = 225°; site F: $n = 54$, mean = 221°; site G: $n = 15$, mean = 213°; site H: $n = 20$, mean = 223°; totals: $n = 178$, mean = 221°. No measurements were taken at site B.

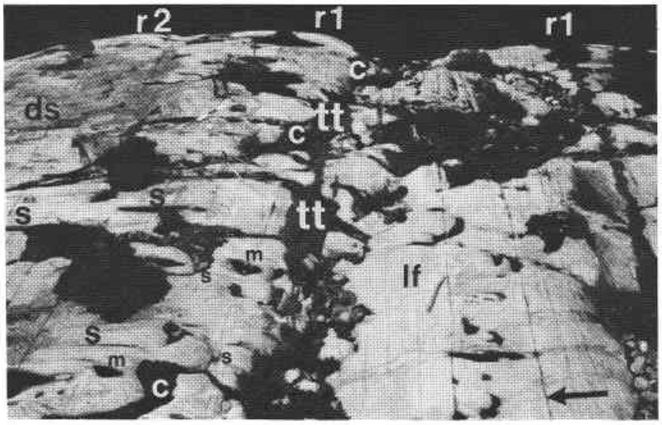

FIG. 7. Study site A showing four zones: (*i*) transverse troughs (tt); (*ii*) lee face (lf); (*iii*) riser slope with two orders of rock rises (r1, r2), crescentic forms (c, including sichelwannen), muschelbrüche (m), and open spindles (s); and (*iv*) distal slope (ds). Rock rises are defined by joint pattern. Flow from right to left. Scale bar (arrow) =5 m.

dimensional, nondirectional undulations. Distinct erosional marks are rare or absent on this slope. Where marks do occur, they are invariably longitudinal, predominantly indistinct extensions of the horns of sichelwannen on the riser slope.

A brief interpretation is presented here in preparation for a more general interpretation of site-scale features.

The transverse trough strongly influenced the distribution of superimposed forms. We speculate on how this might have resulted from the interaction of local topography and flow once the trough was created but do not explain how the trough formed in the first place.

We assume that the formative flows had high vorticity for the following reasons: the evidence for vortices in the numerous sichelwannen (Allen 1971); the probability of horseshoe vortex generation (Karcz 1973; Maull and Young 1973; Shaw and Sharpe 1987) around bluff obstacles in the form of the numerous rock drumlins; and, similarly, the formation of vortices around boulders projecting from the overlying ice (Hjulström 1935; Dahl 1965; Shaw 1983). Vorticity is a conservative property, and vortices are expected to be advected with the fluid within boundary layers. For vortices to erode they must impinge on the bed or walls of the flow (Shaw 1988*a*).

With the idea of vortices in a flow boundary layer, we now consider the general flow structure in and around a transverse trough and extend our preliminary discussion on erosional-mark genesis. Flow separation almost certainly took place downflow from the rim of the lee face, and the return flow at the base of the separation eddy must have eroded this face. This precludes deposition in the separation zone, which demonstrates the vigour of the sediment-transport processes; sedimentologists expect to find deposition immediately downflow from a separation line.

Reattachment of the boundary layer on the riser slope of the transverse trough accounts for the intensity of sichelwannen developed there. Vortices impinging on the bed in this zone gave rise first of all to muschelbrüche, which subsequently deepened to form sichelwannen (Fig. 5) (Allen 1971). The closely clustered sichelwannen may represent numerous impinging vortices or the formation of secondary forms by vortices shed from primary features. The preponderance of sichelwannen is to be expected, as they are longer lived than the transitory muschelbrüche.

Flow near the bed at the foot of the riser slope was funnelled into shallow stoss-side furrows, into which it carved small-scale sichelwannen. The regular spacing of these furrows, which gives the base of the riser slope a regular, sinuous appearance, is not related to an obvious bedrock structure and was most probably controlled by flow dynamics, although we offer no mechanism accounting for this.

Higher on the riser slope, vortex impingement would have been at a shallower angle, and vortices from higher in the flow were probably of relatively large diameter, having formed some distance upflow. Resulting muschelbrüche are consequently larger because their width is determined by the width of the formative vortices (Fig. 5). This in turn explains the relatively large size of subsequent sichelwannen. The density of sichelwannen in this area is also lower than that in the transverse trough, suggesting fewer impinging vortices.

Flows bifurcated where furrows are truncated in the downstream direction by sichelwannen. Flow bifurcation and convergence, like that inferred for stoss-side furrows, appear to have been complementary and will be emphasized later in a general model of the assemblages of erosional marks. The cause or causes of bifurcation are not obvious. It is possible that the high-energy flows that form the furrows become unstable, and energy dissipation, in the form of violent turbulence, produces muschelbrüche that evolve rapidly to sichelwannen. Alternatively, vortices at higher levels in the flow may be drawn to the low-pressure zone of high-velocity fluid and dive to the bed in the furrows. The furrow flow would then be deflected around the impinging fluid in the manner of flow deflection around a submerged jet impinging on a wall or bed; the impinging vortex itself becomes an obstacle to flow. Furrows at site A cannot be traced downstream of the large sichelwannen that truncate them, which suggests that bifurcation is explained better by instability than by vortex impingement.

Flow over the distal slope was generally parallel to the bed rather than convergent on it. This flow configuration is not conducive to vortex impingement, with the consequence that distinct erosional marks are related more to attached vortices shed from upstream sichelwannen. However, the lower elevation of the distal slope indicates relatively high rates of erosion there, and its undulating relief may be typical of an erosional regime for slopes lying closely parallel to flow lines. The intensity of erosional marks on upstream-facing bed slopes, where vortices are expected to impinge on the bed, may be a corollary to this argument.

This brief discussion on the assemblage of erosional marks and detailed surface forms in an area of mainly transverse relief features serves as a starting point for a very general and almost entirely kinematic interpretation of the formative flow conditions. We continue to build on it with the introduction of further examples from the other sites.

Site B (NTS 41 H/14; UTM 994848)

At site B, there is an extremely complex arrangement of sichelwannen, muschelbrüche, and spindle forms. But, repetitive patterns of conjugate sichelwannen dominate the bird's eye view (Fig. 8*a*). They are preferentially clustered on the upstream slopes of rock rises. In this respect, there is similarity between sites A and B.

Broad, water-filled or vegetated transverse troughs (tt, Fig. 8a), much larger than those at site A, extend laterally several tens to hundreds of metres. They are asymmetric in flow-parallel profile; the upstream-facing slope, the proximal slope, is steeper than the distal slope.

Clustered conjugate sichelwannen define associated, teardrop-shaped rock drumlins (Fig. 9) (Shaw and Sharpe 1987). These residual rock ridges are blunt at the upstream end where they form the medial ridge of a sichelwannen. By contrast, they are sharply pointed at the downstream end where the ridge is truncated by the rims of adjacent sichelwannen.

The streamwise spacing and width of the conjugate sichelwannen determine the length and width of the rock drumlins. On the proximal slope, where sichelwannen are close together, the rock drumlins are short; beyond the crest of the rise, longer rock drumlins reflect the wide streamwise spacing of erosional marks. Long, shallow furrows extending downstream from sichelwannen and comma forms delineate the rock drumlins on this gentle, distal slope.

The general pattern described for site B, best exemplified by the bedrock rise in the left-centre part of the photograph and interpretive sketch (Fig. 8), is readily identified on a number of bedrock rises. A more detailed view of a rock rise between transverse depressions shows how rock drumlin shape is controlled by sichelwannen spacing (Fig. 9). Note also how the geometry of the residual ridges or rock drumlins is a direct consequence of the en echelon pattern of sichelwannen.

The influence of topography on the distribution and patterns of s-forms once again points to a formative mechanism involving an interaction between flow structure and bed topography. The en echelon arrangement of sichelwannen and their concentration on reversed bed slopes imply that they are not simply primary forms related to bed defects (Allen 1971). Rather, the en echelon pattern of s-forms suggests that flow bifurcation created longitudinal flow structures, probably vortices, that impinged on the bed to form muschelbrüche. We can imagine deflection of the main flow around an impinging vortex then generated two secondary vortices, one on either side of the primary structure. Secondary muschelbrüche then formed where the secondary vortices became unstable. Finally, the muschelbrüche evolved into sichelwannen. Although this model for the formation of en echelon patterns of sichelwannen may be wrong in detail, the true explanation must be along these lines.

Yet it does not explain either the origins of the primary vortices or the streamwise spacing of the erosional marks. It

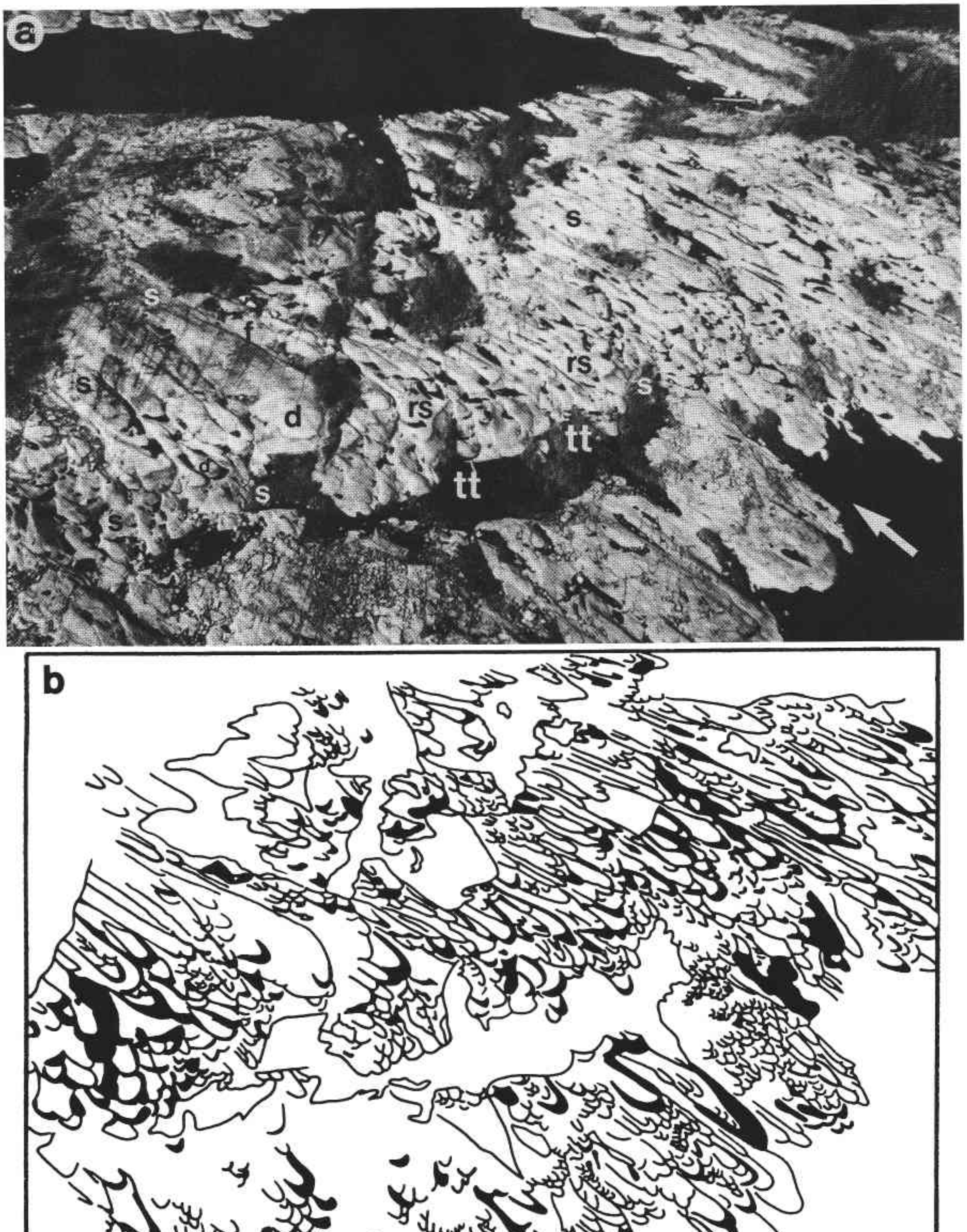

FIG. 8 (*a*) Oblique aerial view of zones of erosional forms on rock rises at site B. Transverse trough (tt) defines upflow end of rock rise (rs) and rock drumlin (d). Sichelwannen (s) and other crescentic forms are common on the stoss side of rises, whereas linear forms, i.e., furrows (f) and spindles (s), are common on the lee side of rises. Flow from lower right to upper left. Scale bar (arrow) = 10 m. (*b*) Schematic representation of area covered by (*a*), illustrating the nested and hierarchical character of the sculpted forms and their zonal distribution. The concentration of crescentic forms on the stoss sides of rock rises and linear forms on the lee sides of rock rises is very clear.

FIG. 9. Detailed oblique aerial view of site B, showing rock rise (rs), rock drumlins (d), furrows (f), transverse troughs (tt), and sichelwannen (s). Flow from bottom right to top left. Scale bar (arrow) = 8 m.

may be significant here that Taylor vortex genesis is expected where the bed is concave upstream of a rise. In addition, for a subglacial setting with reverse bed slopes in the proximal part of the rise, flow would have been strongly convergent as the gap between the basal ice surface and the bed decreased towards the crest. Convergence could have caused frequent impingement of Taylor vortices generated just upstream. This concept accounts for the correlation between sichelwannen spacing and bed slope.

Site C (NTS 41 H/14; UTM 897868)

Site C is located on the stoss end of an island that rises to about 4 m above water level (Fig. 10). The bedrock is coarse-grained, foliated gneiss with folia striking at 145°. Small-scale erosional marks are not common at this site, and those that do occur are subdued and mainly longitudinal, trending at 220° (Fig. 10).

The steeply sloping rock surface immediately above the water is remarkably smooth and lacking in detailed forms. However, the waterline itself is sinuous in response to extremely subtle stoss-side furrows. Where the slope flattens towards the top of the island, there are some incipient muschelbrüche. Beyond this zone a gentle lee slope contains broad, poorly defined open troughs that are not easily placed in the classification of erosional marks, although they seem to be part of a continuum with larger longitudinal furrows.

The most spectacular erosional marks at this site are found along the steep side slopes of the island, where there are nested open spindle forms (Fig. 10). Cavettos are also common along the side slopes.

Site C is located on a rock drumlin bounded by adjacent furrows. The steep proximal slope resembles the riser slope of the transverse troughs at site A (Fig. 7), but the stoss-side furrows, which are subdued and do not contain sichelwannen, appear to have been formed by less powerful flow at site C. Funnelling of meltwater into the bounding furrows explains the high intensity of erosion there and the much lower intensity on the rock drumlin. The shallow, stoss-side furrows represent much less flow convergence than the deep bounding furrows. Convergence results in increased erosion, which, in turn, results in a positive feedback by further increasing discharge through the furrows.

Site D (NTS 41 H/15; UTM 219771)

Site D is situated on a broad, low island with maximum relief of about 2 m. The bedrock is a coarse-grained, garnetiferous granite gneiss. Gneissosity trends at 175° and there is one prominent joint set trending at 130°. Erosion forms trend at 223°.

The low-relief topography is gently rolling, and seen from the air, the upstream end of the island is dominated by extremely large sichelwannen (Fig. 11). Since the site is essentially a low rock rise, sichelwannen are again seen to be clustered on the riser slope. Relatively large muschelbrüche lie downflow from the sichelwannen. The distal portion of the island (the distal slope of the rock rise) is devoid of small-scale forms and exemplifies the nondirectional, undulating surface (Fig. 3*h*). There are, however, broad and shallow longitudinal furrows colonized by grasses in the distal parts of the site (Fig. 11). Furrows and the extended downstream arms of sichelwannen combine to outline the low intervening ridges and rock drumlins.

There are large numbers of cobbles on the erosional surface at site D; many are faceted and striated, and others are slightly

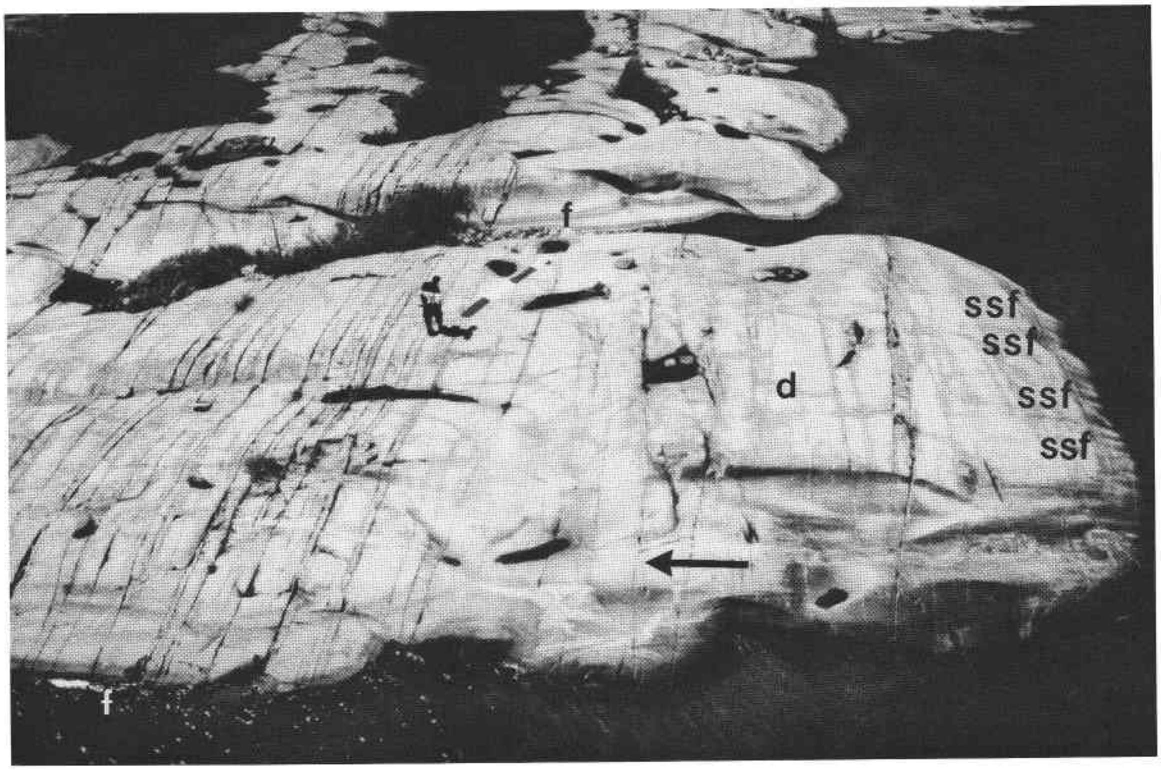

FIG. 10. Oblique aerial view of site C. Note rock drumlin (d), furrow (f), and stoss-side furrows (ssf). Flow from right to left. Scale bar (arrow) = 4 m.

rounded. Less common are large angular boulders. The bedrock is striated and bears small, flute-like erosional marks with a rough rather than smooth surface texture.

Site D is notable for the paucity of small-scale meltwater erosional marks and the large size of the sichelwannen and muschelbrüche. On a broad scale, however, it has much in common with other sites, for example, the clustering of sichelwannen on the upstream side of bedrock rises and the appearance of more subdued, predominantly linear forms distally.

The absence of smaller scale erosional marks on the lee slope at site D may be explained if their existence depended on vortices generated by local sichelwannen. The small number of sichelwannen limits the potential for the generation of small-scale secondary forms. On the other hand, the broad, grass-filled troughs might well relate to broad-diameter vortices extending from the large, proximal sichelwannen.

The large number of striated cobbles and boulders at site D may indicate relatively low flow power or a short duration of flow at this site. A relatively weak flow may have been incapable of moving all the debris, or one of short duration may have had insufficient time to flush debris from the ice and bed; consequently more cobbles and boulders remain. Striated and faceted cobbles and angular boulders together with fresh striation on the bedrock indicate a minimum of postglacial weathering and erosion. Wave action has had virtually no effect on the bedrock surface or clasts.

Site E (NTS 41 H/14; UTM 128830)

Site E is located on a broad, low island with a relatively steep proximal slope and a gentler distal slope. The height of the island is about 2 m above water level at its proximal end and only about 1 m over much of its distal parts. The bedrock is a weakly jointed, medium- to coarse-grained gneiss with included, stretched mafic fragments. Prominent mafic dykes cut across the gneissosity (Fig. 3*e*), which trends at about 110°.

The study site lies at the distal end of the island, where spectacular longitudinal s-forms trend at 221°. Spindle forms, broad furrows, and muschelbrüche are the predominant erosional marks on the relatively flat distal slope (Fig. 3*e*). On the flanks of the island, transverse forms, sichelwannen, and comma forms are better developed, especially downflow from prominent furrows. These combine to form deep troughs that bound rock drumlins.

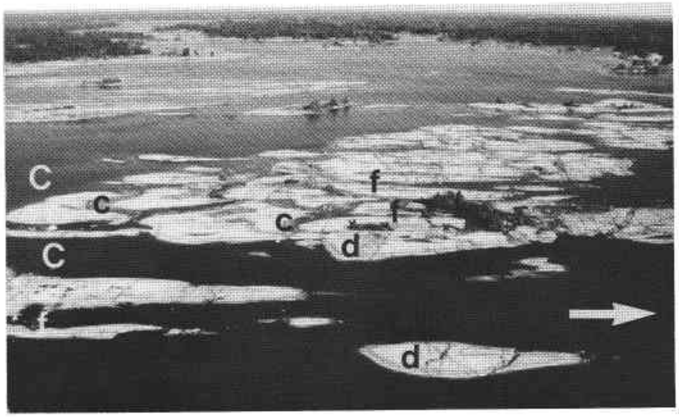

FIG. 11. Oblique aerial view of site D, showing cluster of rock drumlins (d) and furrows (f). Crescentic scours (c) define the upflow end of rock drumlins. A cluster of rock drumlins defines a large-scale rock rise with crescentic scours on the upflow (left) end. Flow from left to right. Note a scattered boulder lag. Scale bar (arrow) = 15 m.

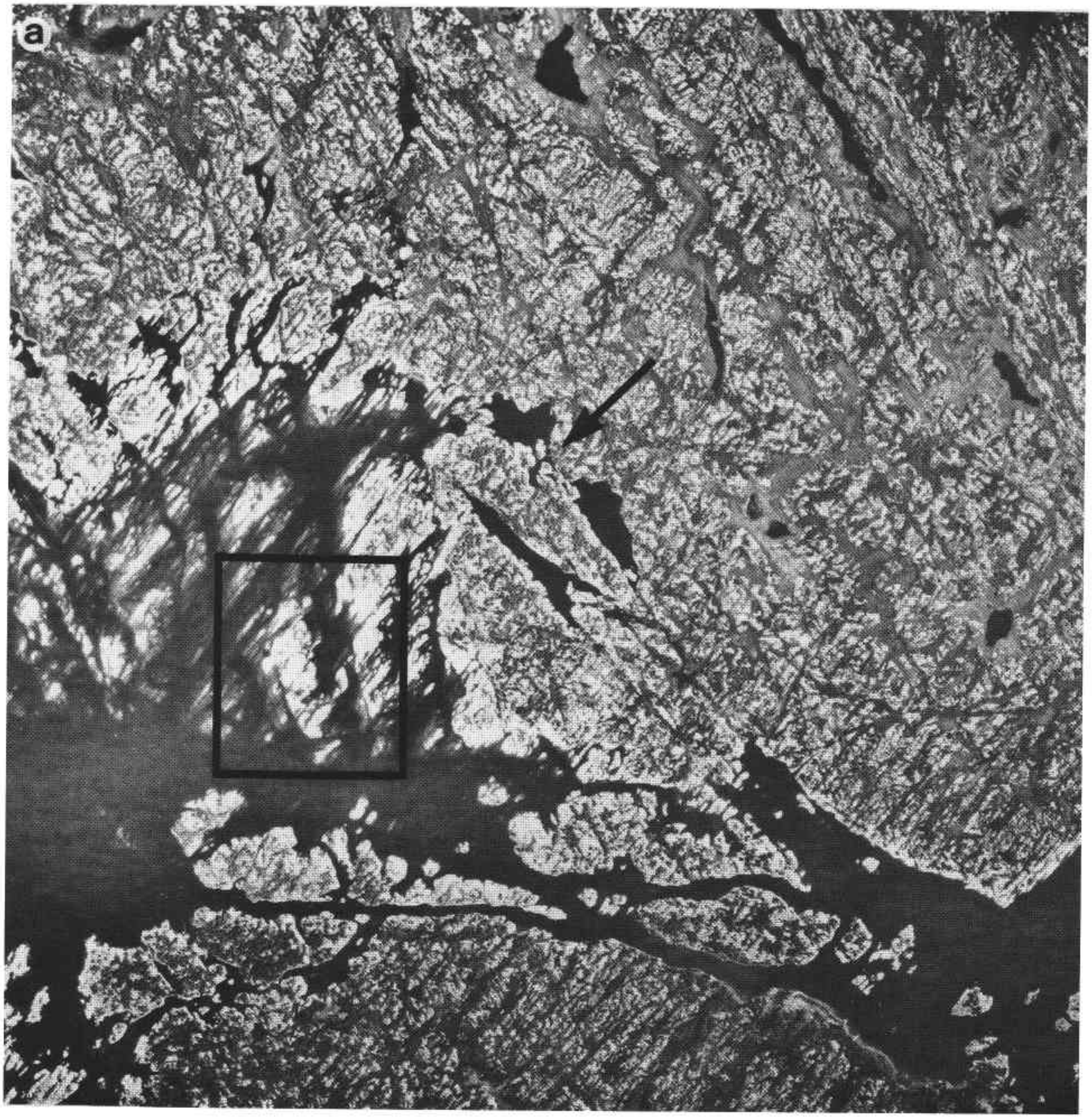

FIG. 12. (*a*) Airphoto of Henvey Inlet area, showing strong (central area) and weaker (lower area) expression of rock drumlins and furrows, indicating southwest flow direction. Rock structure trends southeast in this area. Outlined area is enlarged in (*b*). Scale bar (flow direction arrow) = 0.5 km. North at top of photo. Ontario Ministry of Natural Resources airphoto 9-4529-36-192.

In keeping with previous findings, longitudinal forms are well developed on the distal slope at site E. Flow lines were probably roughly parallel with the bed, and flow impingement was probably at a shallow angle. Not surprisingly then, following previous interpretation, spindle forms and shallow furrows are common. The dominance of muschelbrüche over sichelwannen in this zone may indicate a relatively slow rate of formation of erosional marks. Alternatively, a short duration of flow may be responsible, whereby muschelbrüche did not evolve to the point where flow separation produced sichelwannen.

But along the flanks of the island, downstream from prominent flutes, sichelwannen and comma forms are common, supporting the general conclusion that these more mature forms, which generate their own secondary flow and are related to higher flow power, were formed where meltwater was "streamed" or funnelled by longitudinal furrows. Note that the island flank is the side wall of a large erosional furrow which is itself part of a larger scale erosional mark higher in the hierarchy.

Subsite-scale forms (metres)

Subsite data were gathered at all study sites, and several observations are noteworthy. Rock rises a few metres across and less than 1 m high possess erosional marks, primarily sichelwannen, comma forms, spindle flutes, and muschelbrüche arranged systematically with respect to local relief. Sichelwannen and comma forms flank local rises, whereas spindle

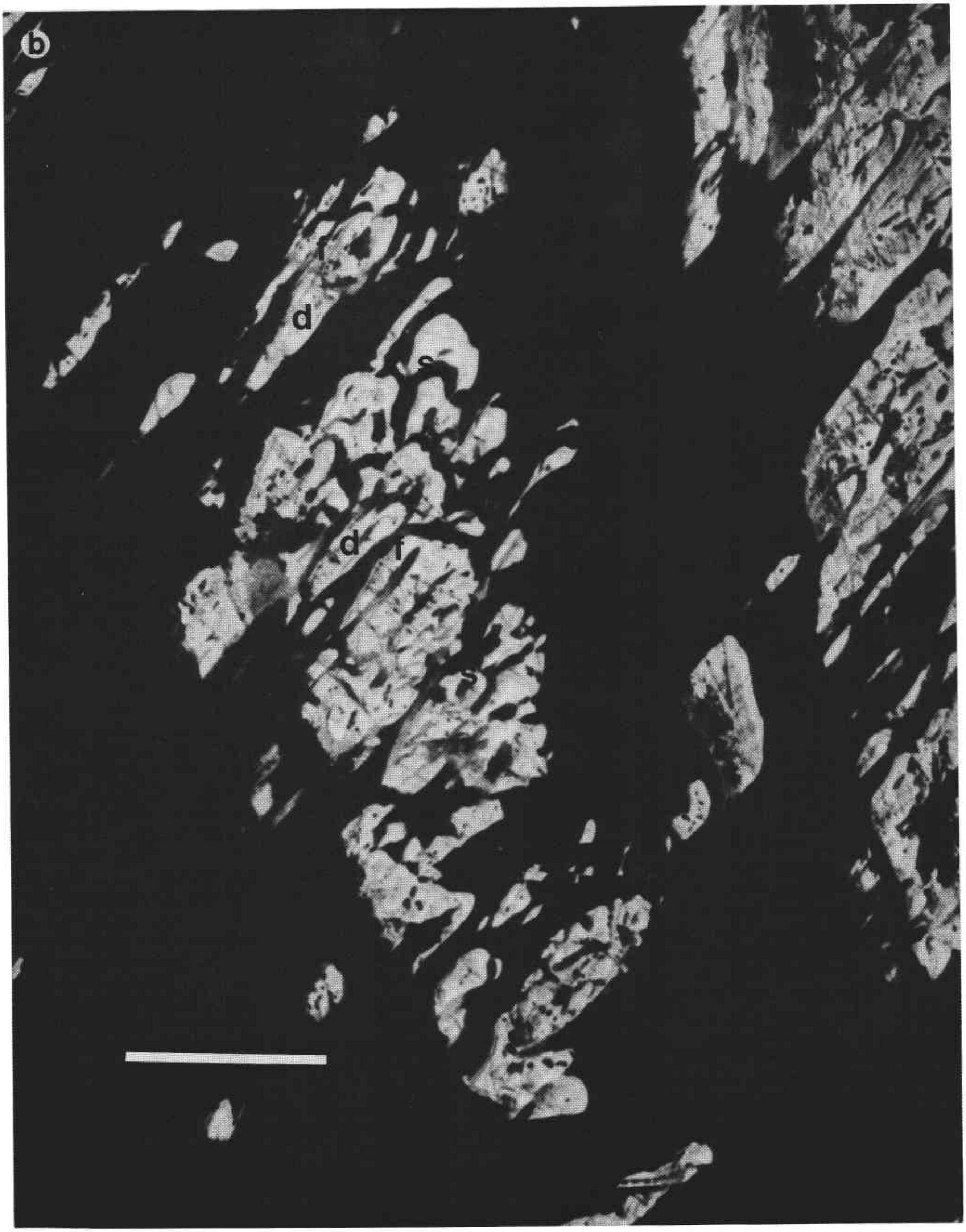

FIG. 12 (*concluded*). (*b*) Detail of (*a*), showing island group, rock drumlin cluster at site D. Note longitudinal rock drumlin islands (d) and intervening furrows (f). Sichelwannen (s) are outlined by the shoreline. Flow from upper right. North at top of photo. Scale bar = 100 m.

flutes and muschelbrüche were found on the riser slope or on the distal slope.

The smallest s-forms range in width from 20 to 40 cm and indicate small-scale flow structures (vortices) of similar width. The widths of sichelwannen, ranging between about 0.2 and 50 m, approximate the widths of larger scale flow structures. We see that flow structures of very different sizes produced similar forms. This is the reason that the classification of s-forms is not dependent on scale.

Local-scale forms (100–1000 m)

There are several forms defining a local scale of bedrock sculpting along Georgian Bay: longitudinal islands (rock drumlins), furrows, and transverse rises. These forms may be just recognizable on high-level airphotos (1 : 15 840 scale and smaller), but they are readily apparent from low-level airphotos and when viewed from a helicopter (Figs. 11, 12*b*).

Longitudinal islands and rock drumlins at the local scale are common along the Georgian Bay coast. Rock drumlins are found individually or clustered in groups (Figs. 11, 12*b*) which show a strikingly parallel, southwest orientation across individual airphotos (Fig. 12*a*) and across the study area (Fig. 6). These forms are 100–1000 m long, approximately 10–50 m wide, and up to 10 m high. They have broad, rounded leading edges and taper rapidly to a pointed downflow end. Depending on water level, rock drumlins may be found as isolated islands (Fig. 11) or as residual rock ridges defined by crescentic depressions extending downflow into the main furrows of enormous sichelwannen (Fig. 12*b*). Rock drumlins are found in groups with individuals aligned parallel to one another or in an en echelon array (Fig. 11). Smaller forms are usually superimposed on their surfaces (Figs. 4, 9).

Furrows form longitudinal troughs parallel to rock drumlins (Figs. 4, 10). They appear on airphotos as a fluting pattern defined by water-filled troughs or vegetated lineaments, 100 m to several kilometres in length, 1–10 m wide, and up to 10 m deep. They are remarkably straight (Figs. 6, 12*a*) and combine with the rock drumlins to produce a strikingly parallel regional orientation, with inferred flow to the southwest (Fig. 12*a*).

Rock rises, the third type of feature defined at the local scale, are defined by steep stoss ends and gently sloping lee slopes (Figs. 7, 9). Rises have a wavelength of 50–100 m and a usual amplitude of 2–5 m, rarely exceeding 10 m. Several smaller scales of transverse rises may be superimposed on the local-scale rises (Fig. 7). Whereas crescentic forms, primarily sichelwannen, comma forms, and cavettos, usually occur on the stoss slope of rises, linear forms, such as spindles, flutes, and furrows, are eroded on the lee slope (Figs. 7, 8, 9, 11). Transverse rises on the local scale occur at structural discontinuities in bedrock, usually at joint sets (Fig. 7), but this is not always the case at smaller scales (Fig. 3*d*). Rock drumlins and furrows at the local scale cluster on the stoss sides of transverse rises (Figs. 11, 12*b*).

Regional-scale forms (1–10 km)

At the regional scale, first-order s-forms, measuring hundreds of metres to tens of kilometres in length and a minimum of tens of metres in width, are discernible in airphotos (Fig. 12*a*). The most common types of erosional features at this scale are strong linear forms, primarily rock drumlins and intervening furrows. These forms are brought out on photographs by vegetation in the low furrows between the bare rock drumlin ridges. At some localities first-order sichelwannen and other curved or crescentic forms can be discerned in airphotos where they are highlighted by water along the shores of lakes and ponds (Figs. 11, 12*b*) or by vegetation in inland locations.

In the area close to the northern boundary of the Grenville Front the southwest trend of the strongly foliated bedrock generally lies parallel to the regional paleoflow direction, roughly southwest. Here, it is difficult to differentiate between flow indicators and structural–lithological bedrock elements at the regional scale on airphotos. Hence there is an apparent paucity of flow-sculpted features west of the Main Channel, French River (Fig. 6). Where structural and lithological elements of the bedrock trend towards the southeast, for example in the area south of the Key River, flow-sculpted features are mapped with more confidence (Fig. 12*a*).

A stoss and lee relationship exists at the regional scale where meltwater erosional forms crosscut bedrock structure. Bedrock bosses, or rises, commonly exhibit a smooth, straight to gently undulating stoss slope (the meltwater-eroded boundaries of lithological units or structural elements such as faults or joints) and a more broken or saw-toothed lee slope (the result of plucking). Potholes are common on lee slopes, although even the largest ones are not discernible in airphotos.

The distribution of regional-scale s-forms in the study area reflects the relief of the bedrock surface on which they occur. Where stong linear patterns are identified in the airphotos (Fig. 12*a*), topographic relief generally exceeds 10 m. A ''rough'' bedrock surface was apparently sculpted by meltwater. The lower relief (<5 m) bedrock areas adjacent to much of the shoreline of Georgian Bay show weaker regional-scale linear elements.

Generally, smaller scale erosional forms cannot be discerned in conventional airphotos. But we find them on the ground throughout the study area, although they are best developed on smooth bedrock surfaces of relatively little relief and on the upflow side of rock rises (Figs. 4, 8, 9).

The orientation of the linear erosional forms measured from airphotos gives the regional flow field (Fig. 6). Flow direction was very consistent, towards the southwest, with only a slight convergence into the Georgian Bay basin. This regional flow consistency is discussed later.

Discussion of scales of erosional forms

Georgian Bay erosional forms are identified and described at several scales, from the subsite (metres) to regional (tens of kilometres). They are arranged systematically with respect to relief; similar forms are observed on similar slope aspects over a broad range of scale (compare sichelwannen in Figs. 9 and 11). This ordered topographic arrangement of forms gives information on flow geometry (e.g., vorticity, flow separation, flow convergence, and bifurcation) and its interaction with bed topography.

How are the erosional forms at the regional scale related to those at smaller scales? At the site scale, vortex impingement on the bed is inferred to spawn an en echelon sequence of forms downflow from sites of flow concentration (Fig. 13). For example, at sites A and B, sichelwannen concentrated on the riser slope are transitional upslope to nested sichelwannen, spindle flutes, and muschelbrüche. Thus a large-scale flow structure (a longitudinal vortex) impinging on the bed spawns a predictable series of erosional forms. By equating s-form scale and the size of eroding flow structures, we suggest that large-scale sichelwannen (their crescentic outlines bound shield-

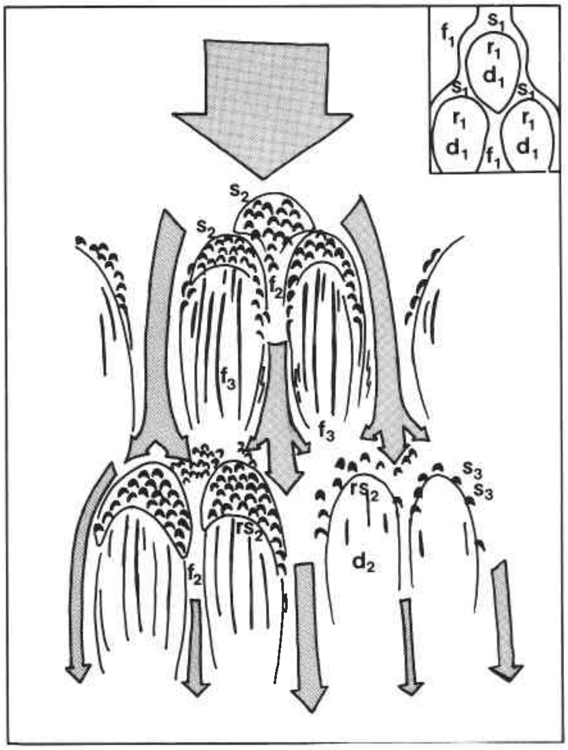

FIG. 13. General interpretive diagram showing conditions of formation of various scoured forms. Flow indicated by arrows. Inset shows first-order forms: rock drumlin (d), riser slope (rs), sichelwanne (s), and furrow (f).

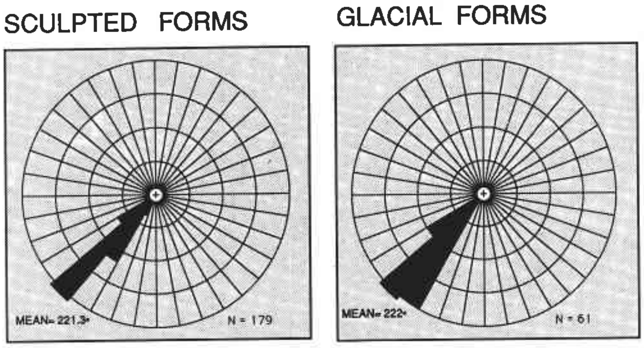

FIG. 14. Paleoflow and glacial flow directions from seven study sites (see Fig. 5 for locations), and aggregate values presented as rose diagrams. Note the consistency of paleoflow direction and the close correlation with ice-flow-direction indicators.

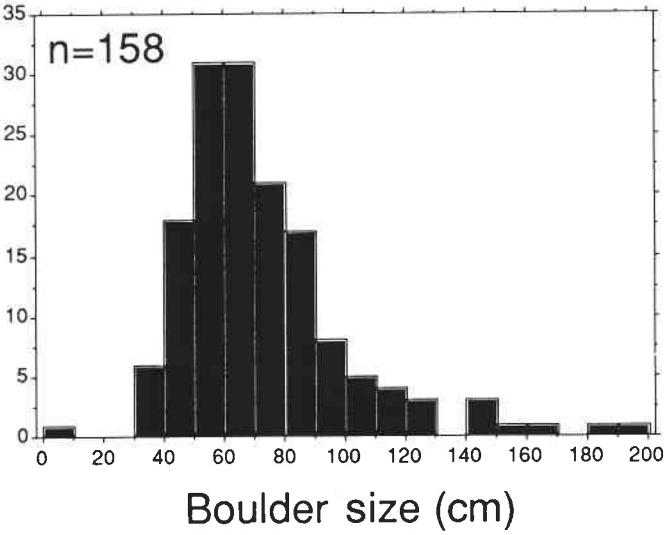

FIG. 15. Histogram of boulder sizes measured at seven study sites (see Fig. 5 for locations).

shaped rock rises at site D, Fig. 11) were probably initiated by regional-scale flow structures (Fig. 13). These structures were caused presumably by flow funnelling through regional-scale longitudinal furrows (Fig. 12*a*). This flow organization provides a genetic link, for example, between longitudinal furrows (regional scale) and spindle flutes (site scale). Thus, the distribution of erosional forms is controlled by bed topography, the different scales of flow structure, and, presumably, by some feedback between the two.

Regional patterns of longitudinal furrows are easily recognized on broad, relatively level surfaces, where they cut across bedrock structure. Furrows are less clear or difficult to distinguish where flow was parallel to bedrock structure; it is difficult to separate the effects of meltwater erosion and other agencies that might enhance linear weaknesses in the bedrock. Nevertheless, it is unlikely that meltwater erosion would have been less effective in areas where flow was parallel to structural weaknesses than where it was perpendicular to them.

Independent of the relationship between flow direction and structural trends, the upflow portions of large lithologic or structural bedrock blocks are marked by large crescentic forms that lead downflow into longitudinal furrows.

In the same manner, spindle forms and comma forms are best developed on upper-level areas of rock rises where bed relief or roughness is low. The upflow portions (e.g., site C) carry sinusoidal forms or stoss-side furrows, which are transitional downflow to shallow troughs and spindle flutes. Thus the formative flow mechanisms appear to have operated over the full-scale range, from site to regional.

Large potholes (Fig. 3*i*) are found at major breaks in slope (usually structural elements of the bedrock) where longitudinal flow structure gives way to flow elements with vertical axes. Where longitudinal flow structure breaks down at smaller scales, transverse troughs and (or) a high density of crescentic forms (conjugate sichelwannen) are produced.

Large, low-relief, upland areas would have allowed stable flow conditions to develop, and this would have promoted the formation of long, regional-scale forms. Their consistent, linear pattern reflects vortex streaming in narrow zones.

Paleoflow estimates

Directional data

We can easily reconstruct the general pattern of flow for the subglacial meltwater floods because s-forms are so widely distributed and well preserved. Paleoflow directions were estimated from two types of erosional forms at each site: (*i*) s-forms; and (*ii*) glacial-abrasion forms, mainly striae and chattermarks. Some s-forms have arms and troughs whose axes deviate from the primary paleoflow direction, so, as for chattermarks, we used an axis of symmetry for the total mark to estimate flow direction. Similarly, we used inferred axis to determine flow direction from asymmetrical forms. Measurements of paleoflow are summarized at each site (Figs. 6, 14). The mean directions from both s-forms and glacial-abrasion forms for individual sites are closely parallel to the alignments of linear features, rock drumlins, and furrows identified on airphotos. A summary of measurements at all sites (Fig. 14) indicates that s-forms, glacial forms, and the total forms have very tightly clustered values about the mean: (*i*) 221° for 179 erosional forms (standard deviation 9°); (*ii*) 222° for 61 glacial forms (standard deviation 6°); and (*iii*) 222° for 240 total forms (standard deviation 12°).

Such parallel flow directions over a broad region indicate a flow response to a regionally uniform potential across at least the 70 km study area. The disregard of the flow for the regional topography leaves no doubt that the s-forms were produced subglacially and the driving potential was directly related to the surface slope of the ice sheet. Thus, the directions obtained for the meltwater and glacial forms are parallel because both flows responded to the same potential gradient. In addition to the regional extent of the flow field, the sculpted forms are remarkably uniform in size and style across a broad area, suggesting that a single, widespread meltwater flood gave rise to the French River s-forms. The internal structure of this regional flow is inferred to have been hierarchical and coherent, producing similar forms at both local and site scales.

Boulder lag

Sculpted rock surfaces are devoid of sediment, with the exception of a sparse, scattered lag of coarse sediment (Figs. 9–12). We measured the axes and noted the lithology and surface features of this lag material at seven study sites. Most of the measured boulders were well rounded, and a large percentage had percussion fractures on their surface. Most boulders are of Superior Province rocks and lithologies from the Sudbury basin, 65 km to the north. A few small boulders of softer lithologies were multifaceted and striated (site D).

The most significant aspect of the lag is its size distribution (Fig. 15). Almost all measured boulders are greater than 0.3 m in maximum diameter, ranging up to 2 m, with a mean of about 0.6 m. The size distribution of 165 boulders is slightly negatively skewed, has a sharp truncation at 0.3 m, and shows few clasts smaller than 10 cm.

We use the size characteristics of the lag to estimate the meltwater flow velocity. Flow competence was evidently sufficient to remove virtually all clasts of diameter less than 0.3 m, and percussion marks on clast surfaces suggest bedload transport by saltation. Velocity estimates, obtained by relating these observations to empirical studies, are between 4 and 15 m/s (Elfström 1987; Maizels 1989).

Discharge magnitude

The assemblage of erosional marks points to regional-scale subglacial floods over the northern part of Georgian Bay. Estimates of flow width (w), velocity (v), and depth (d) are needed to estimate discharge ($Q = wvd$) of these floods.

We estimate the flow depth from the observed height of sculpting on rock rises at the study sites; this is at least 10 m at some sites. Our assumption is that the rock rises were submerged by the floodwaters, but we do not take into account that the ice bed may have conformed approximately to the underlying bedrock topography, rising over high points and sagging above low ground. Nevertheless, our depth estimate is probably a minimum. Flow width was at least 70 km, and possibly greater than 100 km, based on the continuity of sculpting and the consistency and size of s-forms across the study area. Thus, using estimates of velocity v = 5 to 10 m/s, depth d = 10 m, and width w = 70 km, we estimate flood discharge to have been 0.4 to 0.7 × 10^7 m^3/s. This compares closely with other estimates for catastrophic flood discharges: (*i*) glacial Lake Missoula at 2.13 × 10^7 m^3/s (Baker, 1973); (*ii*) Livingstone Lake drumlin field at 0.6–6.0 × 10^7 m^3/s (Shaw *et al.* 1989); and (*iii*) Sable Island tunnel valleys on the Scotian Shelf at 0.45 × 10^7 m^3/s (if all seven anastomosing valleys were operating; Boyd *et al.* 1988).

Conclusions

(1) The distribution and form of erosional marks at Georgian Bay correlate closely with bed topography suggesting that relief is an important factor in their formation. For example, there is a predictable sequence of forms along a traverse from proximal to distal slopes of rock rises: crescentic s-forms are replaced downflow by longitudinal forms.

(2) The geometry and location of s-forms may be explained by an interaction between coherent flow structures and the bed. Aspects of flow scale, vorticity, separation, convergence or funnelling, strength, and direction are inferred from erosional marks and their patterns. In addition, some forms caused flow separation that accentuated the relief by increasing erosional rates. Sichelwannen appear to grow indefinitely by this feedback process.

(3) These inferred attributes of the flow imply subglacial meltwater erosion by powerful flow structures (vortices) at a variety of scales.

(4) Regional mapping of subglacial meltwater forms delimits a broad flow at least 70 km wide.

(5) The Georgian Bay meltwater discharges are estimated to have been similar to those associated with the drainage of glacial Lake Missoula (Baker 1973), the formation of the Livingstone Lake drumlins (Shaw *et al.* 1989), and catastrophic flow through the Sable Island tunnel valleys (Boyd *et al.* 1988), that is, on the order of 10^7 m^3/s.

(6) The Georgian Bay floods had a structural organization producing a hierarchy of similar features or erosional forms at different scales: rock drumlins, for example, occur at the regional scale (>50 m wide), the local scale (10–15 m wide), the site scale (2–3 m wide), and the subsite scale (<1 m wide).

(7) The Georgian Bay floods required the storage of large volumes of subglacial water. The James Bay Lowland, possibly extending into Hudson Bay, north of the saddle in the Abitibi Upland (Fig. 1) was the probable reservoir site. This storage reservoir must have been of vast extent and have taken a long time (>1000 years?) to fill. Consequently, there would have been time for the ice sheet to adjust to the low basal shear stresses, and only a relatively thin and flat ice sheet could have been stable in this area.

(8) This study stresses that some large linear bedforms in glaciated terrain are the product of meltwater erosion, and the conventional view that they are products of glacial abrasion cannot be accepted uncritically. This conclusion arises from two aspects of the study. First, the linear elements are clearly transitional from crescentic forms, which are confidently related to meltwater processes. Furrows at the site scale are straight but carry sinuous forms on their flanks. Second, longitudinal regional furrows are related by form analogy to smaller linear forms, such as spindle flutes, by means of the inferred hierarchy of flow structures. Small vortices produce flutes, and larger vortices or vortex complexes produce furrows.

(9) Maps of the distribution of s-forms could tell us a great deal about the form and behaviour of past ice sheets. Fields of

bedrock erosional marks like those described in this paper, erosional and depositional drumlins, and tunnel valleys and tunnel valley complexes appear to represent subglacial outburst floods on a hitherto unimagined scale. If we knew the paleogeography and timing of these events, we might be able to explain aspects of erosion and sedimentation in areas well beyond the margins of ice sheets. In addition, enormous turbidity underflows of fresh water generated by sediment-laden outburst floods may have disrupted the stratification of the oceans around the ice sheets. Ocean circulation may have been changed with consequent climatic cooling. In this way, outburst floods may have contributed to the maintenance of the ice sheets themselves.

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