

Ice-sheet dynamics and subglacial meltwater regime inferred from form and sedimentology of glaciofluvial systems: Victoria Island, District of Franklin, Northwest Territories¹

T.A. BRENNAND

Department of Geography, University of Alberta, Edmonton, Alta., Canada T6G 2H4

AND

D.R. SHARPE

Geological Survey of Canada, 601 Booth Street, Ottawa, Ont., Canada K1A 0E8

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On Victoria Island, tunnel channels, eskers, and associated fans and extended deposits together constitute channelized glaciofluvial systems. Flutes and drumlinoid ridges, interpreted as residuals left by erosive, catastrophic, subglacial meltwater sheet flows, lie adjacent to these systems. One tunnel channel is described in detail. It exhibits deep scours, a discontinuous thalweg, sculpted margins, and flutes on the downflow side of one wall, features indicative of complex flow and possibly several flow events. The tunnel channel is interpreted as the product of erosion by catastrophic, subglacial meltwater flow in a combined ice–substrate (R/N) channel.

Escher sediments and morphology are used to infer details of the depositional environment and meltwater regime. A continuous esker with fans and extended deposits records seasonally controlled discharge events through an R-channel. These features may also suggest a grounding-line environment, thin ice, and localized ice floatation events. Less well connected ridges also record seasonally controlled meltwater rhythms and were produced within a thinning and stagnating ice mass; the depositional environment may have been in a subglacial R-channel or an ice-walled reentrant.

Differences in the drainage system associated with each glaciofluvial landform, and temporal disconnection between tunnel channel and esker formation, is also suggested by possible paleoflow reversals between inferred catastrophic and seasonally controlled drainage phases. Changes in ice-sheet profiles between events may have been responsible.

Sur l'île Victoria les chenaux-tunnels, les eskers, et leurs éventails et leurs dépôts étendus associés forment, collectivement, des systèmes fluvio-glaciaires chenalisés. À proximité de ces systèmes se trouvent des flûtes et des crêtes en forme de drumlins, interprétées comme étant des lambeaux résiduels de l'érosion créée par les crues rapides émanant de la nappe d'eau de fusion sous-glaciaire. La description d'un chenal-tunnel est présentée en détail. Il est caractérisé par des figures d'érosion profondes, un talweg discontinu, des bordures sculptées et des flûtes sur la paroi affrontant la descente des eaux : ces particularités témoignent de la complexité de l'écoulement des eaux et possiblement de l'existence de plusieurs flots différents. Le chenal-tunnel a été vraisemblablement formé par une crue catastrophique d'eau de fusion sous-glaciaire dans un chenal combiné de glace–substrat (R/N).

Les sédiments des eskers et les formes ont servi à décrypter en détail le milieu de sédimentation et le régime des eaux de fonte. L'étude d'un esker continu, et des éventails et leurs dépôts étendus associés, ont permis d'identifier les événements de décharge contrôlés par le rythme des saisons au travers un chenal-R. Ces particularités suggèrent la possibilité de l'existence d'une ligne de broyage, une glace mince, et la flottaison du glacier localement. Les crêtes marquées de discontinuités reflètent aussi les rythmes saisonniers des eaux de fusion; ces crêtes se sont développées au sein d'une masse de glace immobile qui s'amincissait; les sédiments ont pu s'accumuler dans un chenal-R sous-glaciaire ou dans un réentrant à paroi glaciaire.

Les inversions des paléoflôts dues aux phases de crues dites catastrophiques et des autres décharges contrôlées par le rythme saisonnier permettent d'expliquer les différences dans le système de drainage qui sont associées aux formes des terrains fluvio-glaciaires, et d'apprécier le temps écoulé entre la formation du chenal-tunnel et de l'esker. Il est possible que des changements dans les profils de la calotte glaciaire entre ces événements aient contribué à modifier le système de drainage.

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Introduction

Glacial hydrology and hydraulics have an important impact on ice-sheet behaviour (Paterson 1981). The nature of this impact on Pleistocene ice sheets is being assessed by the study of a variety of landforms, such as eskers (e.g., Hebrand and Åmark 1989; Gorrell and Shaw 1991), tunnel channels (e.g., Wright 1973; Barnett 1990), and drumlins (e.g., Shaw et al. 1989). Direct modelling (e.g., Shoemaker 1992a; Arnold and Sharp 1992) is also helping to reveal the role of meltwater storage and release. With this increasing emphasis on meltwater action, it is pertinent to search for a more detailed understanding of glacial hydrologic systems.

Glaciofluvial landforms and sediments can be used to infer

process. Consequently, it is the aim of this paper to describe and interpret glaciofluvial complexes at three sites on Victoria Island (Fig. 1) and to use these to assess the formative meltwater conditions. Differences in esker morphology and sedimentology and landform associations are used to infer the necessary ice-sheet dynamics associated with their formation. Channelized glaciofluvial complexes are the focus of this paper, but streamlined forms are discussed where appropriate. It is demonstrated that these complexes were formed by meltwater in subglacial, grounding-line, or reentrant environments, under both active (early) and stagnant (late) ice conditions. Meltwater processes modified the landscape and the behaviour of the ice sheet across eastern and southern Victoria Island (Sharpe 1992a). In turn, ice-sheet dynamics influenced glaciofluvial landform styles.

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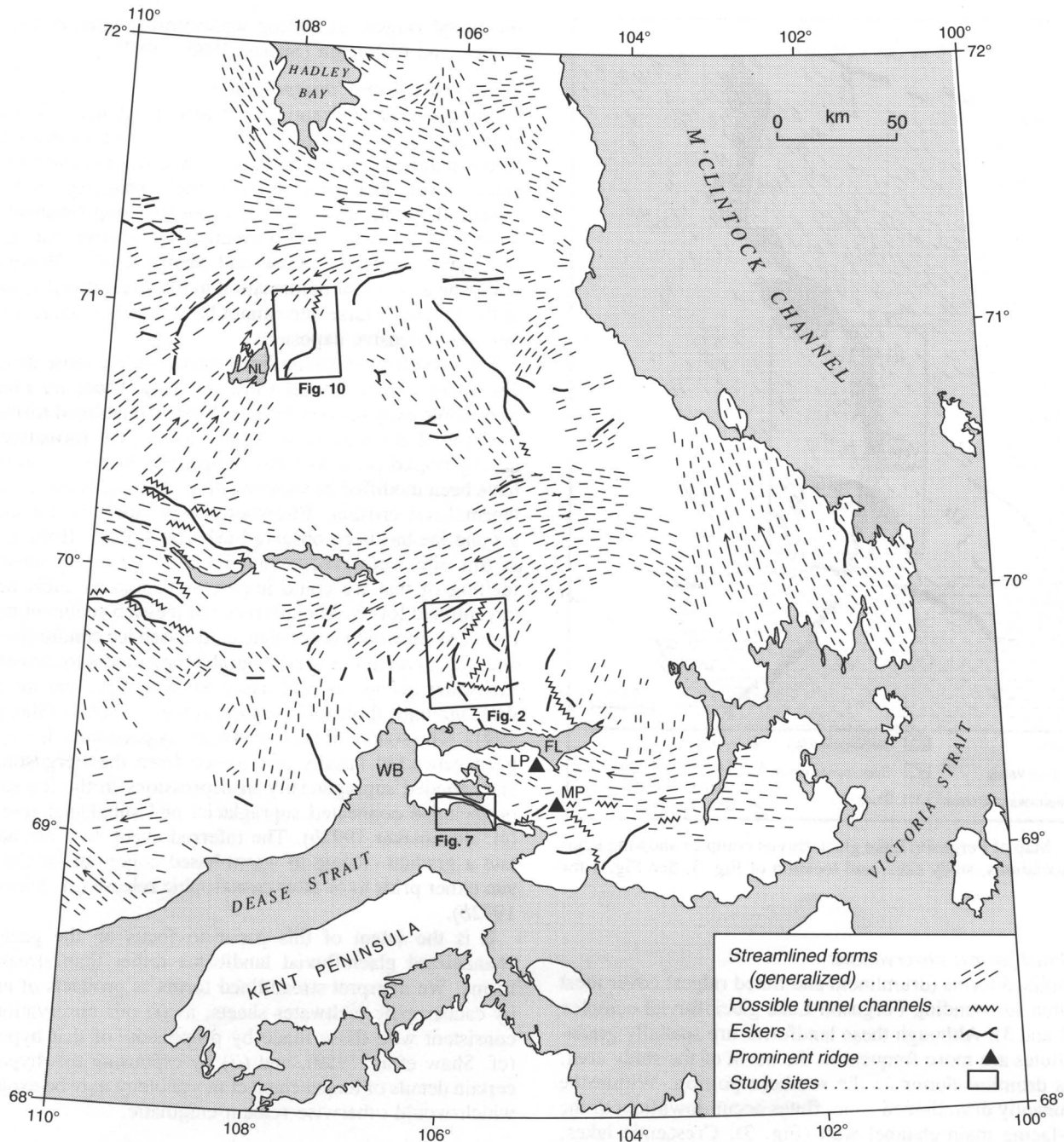


FIG. 1. Location map showing generalized patterns of streamlined forms, tunnel channels, and eskers on southern and eastern Victoria Island, N.W.T. Boxes show location of Augustus Hills glaciofluvial system (Fig. 7), Ferguson lake glaciofluvial complex (Fig. 2), and Namaycush Lake glaciofluvial system (Fig. 10). FL, Ferguson Lake; LP, Lady Pelly; MP, Mount Pelly; NL, Namaycush Lake; WB, Wellington Bay. Modified from Fyles (1963) and Sharpe (1992c).

Ferguson Lake glaciofluvial complex

Environment—landform associations

Ferguson Lake glaciofluvial complex extends about 55 km in a north–south arc, north of Ferguson Lake (Figs. 1 and 2). It may be associated with a glaciofluvial system extending northwest through Mount Pelly and Lady Pelly, south of Ferguson Lake (Fig. 1). The northern part of this system trends parallel and then obliquely to a diverging field of streamlined forms with a northeast–southwest orientation (Figs. 1–3). Approximately 15 km north of Ferguson Lake a smaller esker –

tunnel channel system trends obliquely to the major system (Figs. 1 and 2). South of this intersection streamlined forms are less obvious and forms transitional between streamlined and transverse ridges are draped by marine sediments (Fig. 2). Marine limit crosses the area irregularly, at ~150 m asl.

A sparsity of natural exposures and a possible bias toward sandy sections mean that interpretation is based on description of each landform, the landform associations (Figs. 1–3), and limited sedimentary logs (Figs. 4 and 5). Each landform is described and interpreted separately. Finally, the most probable sequence of events is proposed.

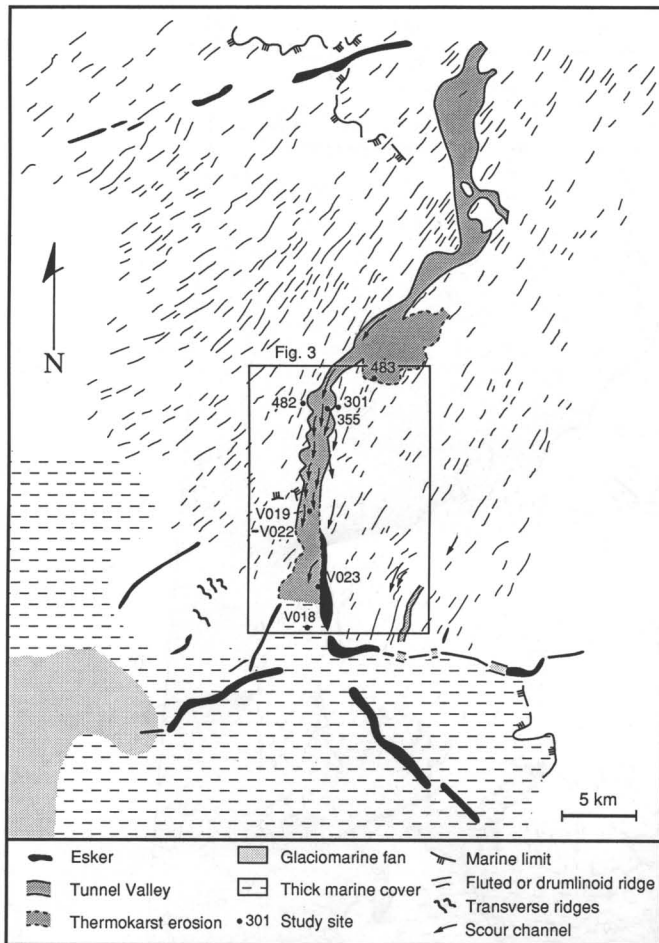


FIG. 2. Map of Ferguson Lake glaciofluvial complex showing landform associations, study sites, and location of Fig. 3. See Fig. 1 for location.

Streamlined forms: observations

Streamlined forms (drumlinoid and fluted ridges) cover most of the area surrounding Ferguson Lake glaciofluvial complex (Figs. 2 and 3). Although these landforms are spatially gradational, flutes are more frequent in the north of the study area, whereas drumlins dominate the southern portion. Within the predominantly drumlinized zone, flutes occur downflow of the upflow-facing main channel wall (Fig. 3). Crescentic lakes, streamlined forms, and ice-marginal fans indicate a flow from the north-northeast.

Flutes separate elongate ridges up to 2.5 km long, 150 m wide, and 8 m high (Fig. 3). They are often occupied by elongate lakes. Crescentic lakes wrap around the proximal ends (north-northeast end) of some fluted ridges. These ridges differ from those described elsewhere (e.g., Shaw 1988); they are less clearly defined, and their crest lines often appear broken or exhibit irregular low sinuosity (Figs. 2 and 3). Underlying stratified, interbedded, and undeformed glaciogenic sediments are up to 40 m thick (Sharpe 1985) (Fig. 5a, sections 482 and 483).

Drumlinoid ridges are relatively straight-crested but generally shorter (<1.5 km) and wider (150–300 m) than the fluted ridges (Fig. 3). They are predominantly spindle-shaped. The lakes associated with the drumlinized landscape vary in shape but are generally elongate with ridge orientation. The sediments within the drumlinoid ridges are similar to those in

the fluted ridges, exhibiting undeformed, interbedded sand, gravel, and diamicton (Sharpe 1985, 1987).

Streamlined forms: interpretation

Elongate and crescentic lakes associated with streamlined fields are inferred to fill scour zones. A lack of deformation in the sediments of streamlined forms, the presence of crescentic lakes that wrap around their proximal ends, and enhanced fluting downflow of a positive step (channel wall) have been used to infer formation by erosive catastrophic meltwater sheets (cf. Shaw and Sharpe 1987). However, a complete absence of deformation in the streamlined sediments at the Ferguson Lake site cannot be claimed, as there were no laterally extensive exposures.

The crest lines of streamlined forms, unlike those described elsewhere, exhibit irregular low sinuosity. There are a number of possible explanations for this. First, streamlined forms near Ferguson Lake may be immature forms, the formative flow having ceased prior to form completion. Second, forms may have been modified by mass wasting, melting of buried ice, or thermokarst erosion. Elsewhere on Victoria Island massive ground ice has been observed (Sharpe 1992a). If the flutings at this site were eroded into ice-rich sediment, subsequent melting of that ice could impart low-sinuosity crest lines to streamlined forms. The inference of ice-rich sediment beneath the ice sheet would necessitate cold-based ice conditions at this site. Such conditions are favourable precursors to catastrophic meltwater events, as cold-based ice would prevent meltwater drainage until threshold conditions were reached (Shoemaker 1991). The source of such meltwater is uncertain. It may have been generated basally and up-ice from the Ferguson Lake site, ponded supraglacially in depressions in the ice surface, or included connected supraglacial and subglacial reservoirs (cf. Shoemaker 1992b). The inferred event does not necessitate a gradual change to warm-based conditions at the study site either prior to or after catastrophic release (cf. Shoemaker 1992b).

It is the intent of this paper to focus on the genesis of channelized glaciofluvial landforms rather than streamlined forms. We interpret streamlined forms as products of erosion by catastrophic meltwater sheets, as (i) our observations are consistent with those made by proponents of that hypothesis (cf. Shaw et al. 1989), and (ii) by espousing this hypothesis certain details of tunnel channel morphology may be explained, which would otherwise remain enigmatic.

Tunnel channels: observations

The main channel (45 km long, 1–2 km wide, and about 30 m deep) north of Ferguson Lake is sinuous, as are other, smaller channels adjacent to it (Fig. 2). These channels cross-cut the streamlined field and are incised into glaciogenic sediment (sections 482 and 483, Fig. 5a). Immediately downflow of the channel margins (to the southwest) flutes persist in a zone otherwise predominantly occupied by drumlinoid ridges (Fig. 3). A fluted sedimentary lobe appears to extend from the eastern margin of the main channel. Section 301 is exposed in this lobe (Fig. 2). Twelve or 13 rhythmic sequences (0.2–1.5 m thick), cross-laminated medium to fine sand, fining up to silt or clay, are observed. Paleoflow was toward the east. The section is capped by diamicton and is below marine limit.

Morphology of the main channel is complex. Channel thalweg is discontinuous, and the margins are not parallel but rather exhibit pronounced scallops along the western wall (Fig. 3). Within the scallops, crescentic lakes fill the deepest

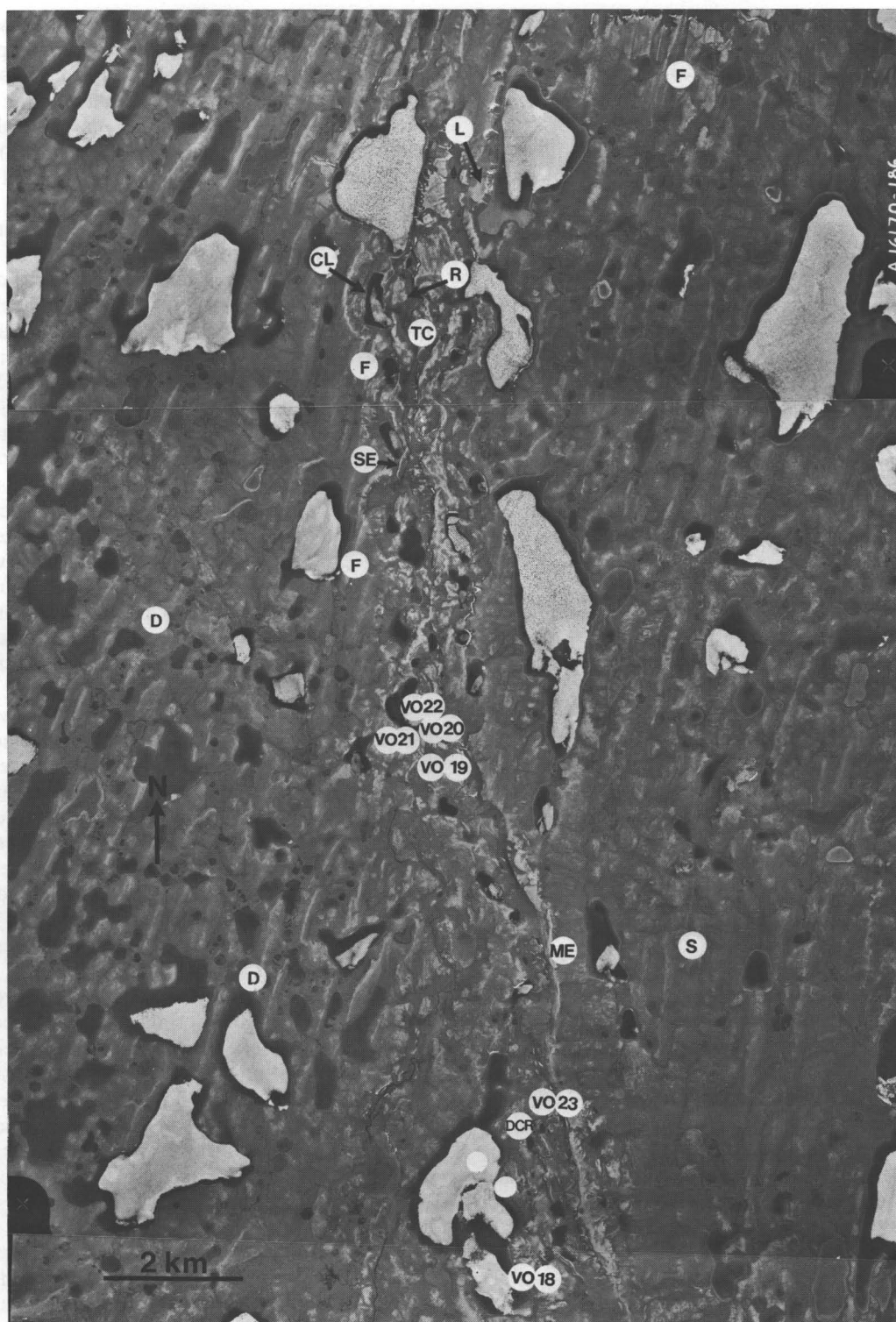


Fig. 3. Air photograph mosaic of Ferguson Lake glaciofluvial complex with section locations (VO18–VO23). Flow from the north-northeast. CL, crescentic lakes within tunnel channel; D, drumlinoid ridges; DCR, double-crested ridges; F, flutes; L, lobe adjacent to tunnel channel; ME, major esker; R, residual hills within tunnel channel; S, subdued streamlined forms; SE, smaller eskers within tunnel channel; TC, tunnel channel with scalloped margins. Air photographs A16170-186, A16170-187, and A16170-188 ©16 July 1958 Her Majesty the Queen in Right of Canada, reproduced from the collection of the National Air Photo Library with permission of Energy, Mines and Resources Canada.

channel sections, and residual hills occur at their geometric focus, or offset slightly to the north (Fig. 3). Inset streamlined hills occur at a lower elevation than the surrounding land surface. Section 355 (Figs. 2 and 5a) is exposed in one such feature and exhibits tabular and trough cross-bedded sand,

indicating paleoflows towards the east and northeast. The eastern side of the channel is less scalloped and exhibits more residuals (or less erosion) than the western side. Shallow inset channels, rather than deep scours, dissect the eastern portion of the channel (Figs. 2 and 3).

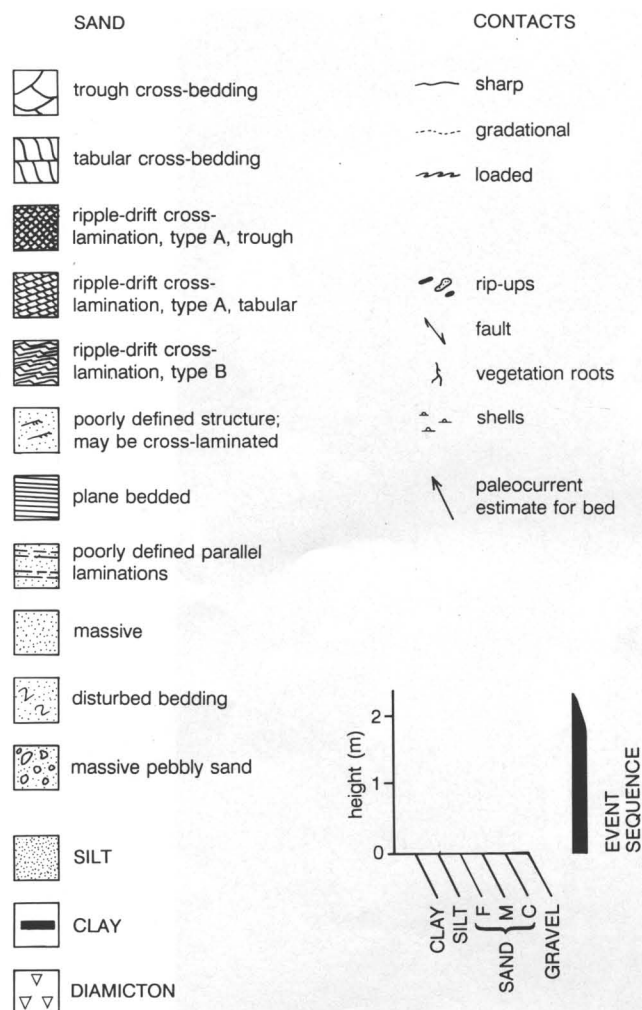


FIG. 4. Legend for sedimentary logs.

Tunnel channels: interpretation

The channels do not appear to be part of a connected fluvial system, which may have existed prior to the last glaciation. In addition, postglacial fluvial activity has been minor (cf. Jenness 1952). Tunnel channels are commonly observed to cross-cut streamlined fields and contain eskers (e.g., Wright 1973). This is the case for the channels at Ferguson Lake. Consequently, the channels at this site are considered to be tunnel channels. Morphology, sedimentology, and context of the main tunnel channel also support this interpretation.

Tunnel channels: form, sedimentology, and context

Given that flutes occur downflow of the western channel wall, it is probable that the channel existed prior to the formation of the streamlined forms. In addition, flutes on the lobe adjacent to the eastern channel wall are oriented parallel to those in the adjacent streamlined field. The sedimentary lobe was, therefore, modified by the event that produced the streamlined field. Consequently, the lobe must predate the formation of this field. Fining-upward rhythmites in this lobe are inferred to represent "overbank" deposits, each rhythmite associated with episodic broadening of the ice tunnel over the tunnel channel prior to fluting formation. The diamicton cap may have been deposited before or after the fluting event and may have also been reworked or winnowed by later marine inundation (section 301 is below marine limit), or by solifluc-

tion. However, the presence of interbedded sand and diamicton within section 482 necessitates their deposition prior to fluting formation. The diamicton cap has a similar composition to underlying diamictons. In addition, the meltwater event inferred to have eroded the flutes may have also left basal ice relatively debris poor (cf. Shaw et al. 1989). Consequently, the diamicton cap was most likely deposited prior to fluting formation.

The scalloped tunnel channel walls are interpreted to be the product of scour, both associated with the meltwater sheet flood event, and during later channelized flow. The deepest scours are along the western side of the channel and are now filled by crescentic lakes (Fig. 3). Inset streamlined hills are inferred to be residuals, either of older glacial sediments (Sharpe 1985) or of glaciofluvial sediments deposited during the formation of the streamlined field. The eastern side of the scalloped portion of the tunnel channel exhibits more residuals (or less erosion) than the western side. Flow from the north-northeast, which produced streamlined forms, cut across the preexisting tunnel channel. Preferential deposition of the coarsest material carried by the subglacial sheet flow, at points of flow separation or negative steps (channel wall), is inferred for the eastern side of the channel. In addition, cross-beds in a within-channel residual indicate easterly and northeasterly paleoflows. These are interpreted as dunes that may have been deposited by a return eddy generated at the channel wall during the sheet-flow event.

At the Ferguson Lake site, the angle of skew (α) of the negative step (channel wall) is about 160° to the inferred sheet flow. For $135^\circ < \alpha < 180^\circ$, the flow separation bubble produced at a negative step forms a vortex that adds both axial velocity and rotational components to flow (cf. Allen 1982). The length of the separation zone (distance to the point of flow reattachment) is primarily controlled by the relative roughness at the step, determined by the ratio of flow depth (h) to step height (H). At this site ($H \approx 30$ m, $h \approx 10$ m; cf. Shaw 1989), the separation bubble would have been approximately 255 m (160 m if $H \approx 20$; cf. Allen 1982, p. 111, Fig. 3-10). The tunnel channel now has a width on the order of 1 km, but was presumably narrower during the proposed sheet-flow event. The channel is inferred to have been narrower, as sediment was preferentially deposited at the eastern side of the channel during the sheet-flow event, and the channel would have also been eroded by later channelized flow. However, it is probable that the zone of flow reattachment occurred within the tunnel channel. Scour along the reattachment zone may account for the deepest scours at the western side of the channel. In addition, streaming of vortices in a subglacial sheet between streamlined forms upflow would have concentrated scour at intervals across the sheet. This could account for the scalloping of the western wall. Hence, the distribution of scallops may be related to the angle of impingement of the vortices on the western wall and the arrangement of vortices in streams within the formative flow.

Deeper scours at the western side of the tunnel channel are explained primarily as the imprint of vortices within the tunnel channel, contemporaneous with the formation of the streamlined forms. By contrast, the shallower scour channels at the eastern side may have been eroded by subsequent channelized meltwater. In addition, such sediment-charged, high-velocity flows would have enhanced the scallops in the western wall by mechanical erosion and melting of ice-rich sediment (cf. Mathews 1973). Channel walls may have also been modified by later thermokarst erosion.

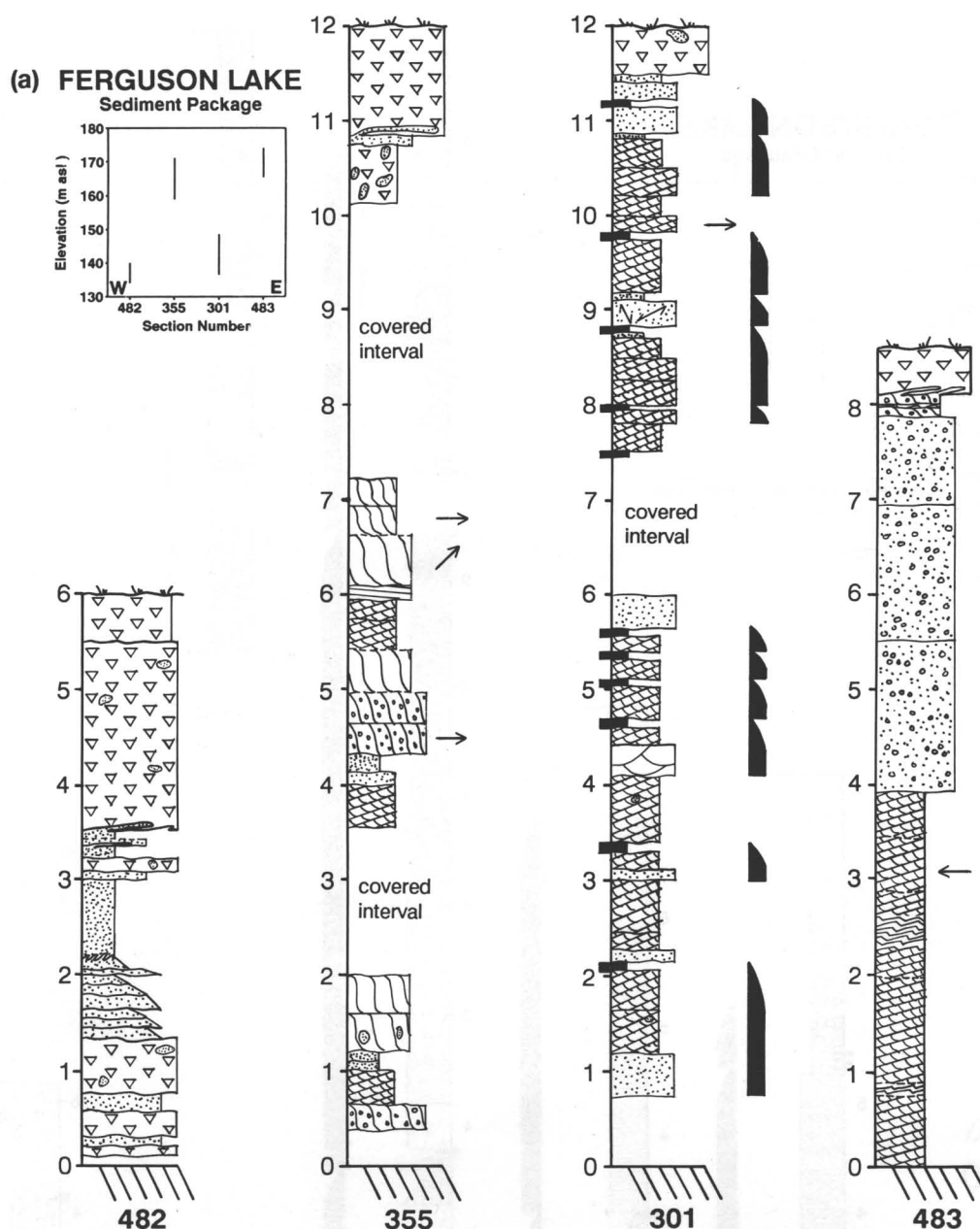


FIG. 5. Sedimentary logs from the Ferguson Lake site, with paleocurrent estimates, event-sequence symbols, and elevation above sea level. See Fig. 4 for legend. (a) Landforms adjacent to and associated with the tunnel channel: fluted ridges (482, 483); residual hill in tunnel channel (355); and lobe adjacent to tunnel channel (301).

Scouring by channelized meltwater has produced a complex tunnel channel morphology. A combined substrate (N-channel; Nye 1973) and ice tunnel (R-channel; Røthlisberger 1972) could explain the observation of a discontinuous thalweg, by allowing intertwined vortices in the channelized flow to impinge upon the base of the ice sheet, as well as upon the basal substrate. Alternatively, or in addition, repeated reoccupation of the tunnel channel after the formation of the streamlined forms, and possibly during successive lesser discharge events, may have further complicated tunnel channel morphology.

Depositional ridges: observations

The depositional ridges are primarily eskerine, although they may include deposits at the eastern margin of the tunnel channel, as previously described. The ridges occur at a num-

ber of scales, from a major esker, running south of the tunnel channel, to smaller discontinuous esker segments within the tunnel channel, to small double-crested ridges west of the major esker (Fig. 3).

The major esker at this site is about 500 m wide and broad-crested and exhibits kettle holes and erratic boulders (Fig. 3). It extends south from the eastern margin of the tunnel channel, continuously for 8.5 km, at which point it is intersected obliquely by a second esker — tunnel channel complex (Fig. 2). It is bounded to the west by a string of lakes. To the east, the topographic gradient is more gradual.

Few natural exposures exist within the major esker (Figs. 3 and 5b). Surficial materials are mainly pebble-sized clasts, whereas underlying beds have a maximum grain size of coarse sand. Section V023 is primarily composed of ripple-drift cross-lamination types A and B (subsequently referred to as

(b) FERGUSON LAKE
Sediment Package

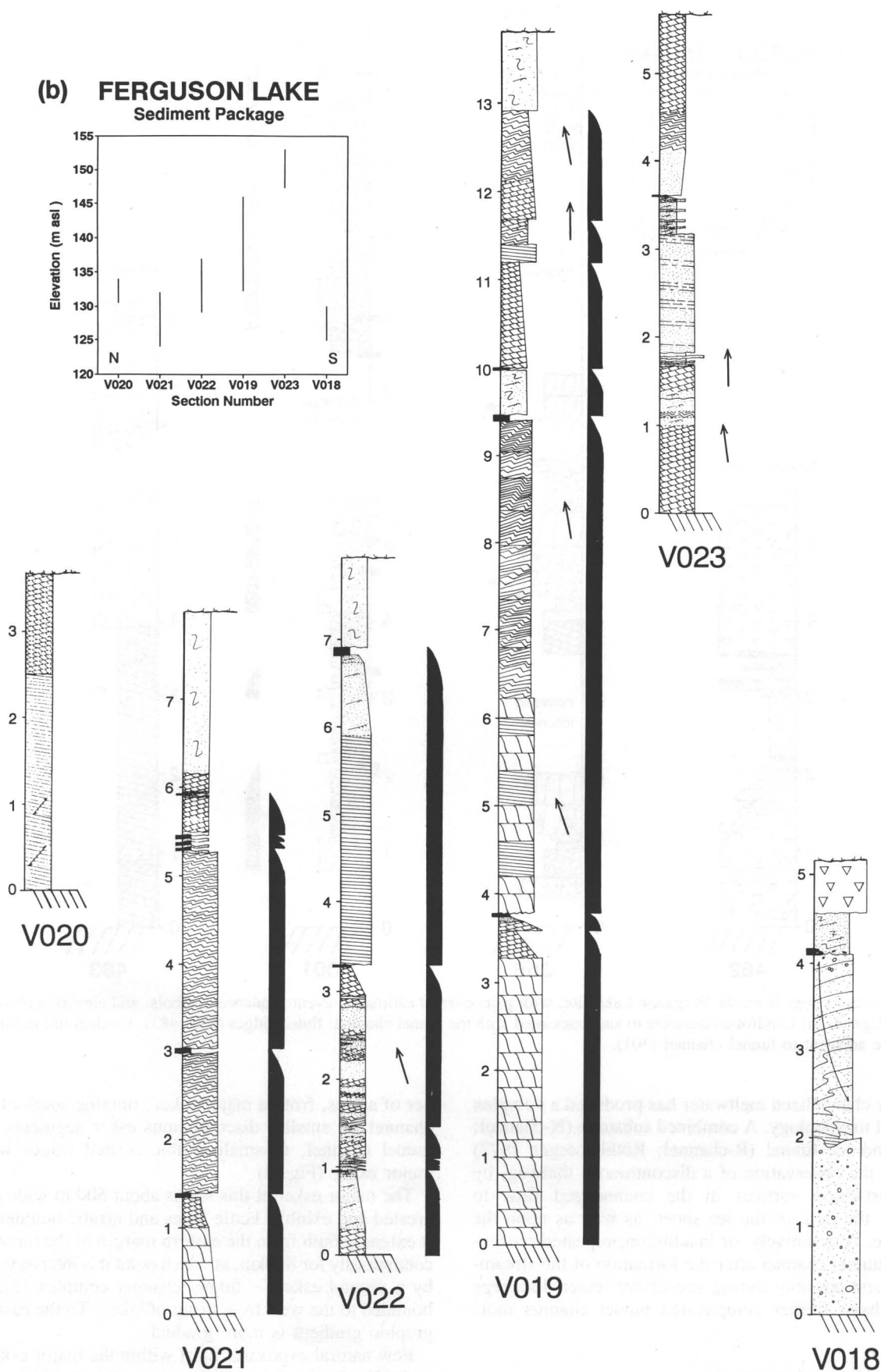
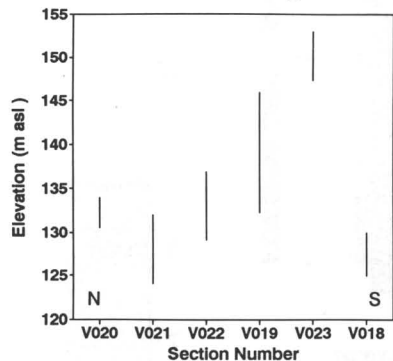


FIG. 5 (concluded). (b) Esker ridge (V019–V023) and double-crested ridge (V018).

RDXL A and RDXL B, respectively), parallel-laminated, and massive sand. One clay band was noted (Fig. 5b). A longer sedimentary record was acquired from the major esker as it extends from the tunnel channel (sections V019–V022, Figs. 3 and 5b). The maximum grain size in these sections is coarse sand. The sections are rhythmically bedded. Each rhythmite is a fining-upward sequence from coarse, medium, or fine sand to silt or clay (see event sequences, Fig. 5b). No extensive faulting was observed. Paleocurrents were towards the north. All sections were located near the western flank of the esker.

Double-crested ridges occur mainly to the west of the Ferguson Lake esker (Fig. 3). Some of these are short, solitary segments up to 100 m long. Others form a dendritic pattern about 2 km long, adjacent to the esker and possibly associated with the west side of the expanded tunnel channel zone (Figs. 2 and 3). The double-crested style is enhanced by small lakes infilling a centre-line depression. Section V018 is a sedimentary sequence from the eastern side of a double-crested ridge (Figs. 2 and 5b). The sedimentary package fines upward and is capped by a rubbly diamicton. Interbedded coarse and medium sand overlies massive coarse sand and granules. The whole section is disturbed by folding and a series of curvilinear reverse faults (Fig. 5b), with displacement towards the centre-line depression.

Depositional ridges: interpretation

Most of the sediments in the main esker form fining-upward rhythmite. Each rhythmite is inferred to represent a waning-flow sequence. Sedimentary structures indicate relatively low energy conditions. Within-rhythmite repetition of structural sequences is inferred to represent responses to pulsed meltwater velocity or suspended sediment supply (cf. Lowe 1988). The clay beds suggest that the meltwater system completely shut down from time to time, although the conduit (R-channel) remained water-filled, during esker formation. The rhythmic sedimentary packages, the thinness of some rhythmites, and the presence of clay caps suggest possible seasonal control on sedimentation and, thus, a supraglacial meltwater source (cf. Weertman and Birchfield 1983; Hebrand and Åmark 1989). The ice sheet must have been warm based or polythermal at this time.

Sections were exposed only in the upper and marginal portions of the main ridge. The relatively low energy conditions inferred from the sediments may be explained either in terms of lateral deposition within a subglacial conduit during waning or low-discharge events, or as the product of subaqueous deposition within an ice-walled channel or reentrant. Marked textural differences between surficial sediments and those exposed within the ridge question the validity of inferring esker genesis primarily from the texture of surficial materials (e.g., St-Onge 1984).

Northward paleoflow in the major esker was approximately opposite to the flow direction inferred for the streamlined forms. Following flooding and bed separation, extremely low ice-surface gradients are expected (Shoemaker 1991). Thus, local piezometric surfaces may have driven subglacial meltwater northward (cf. Shreve 1985). Alternately, meltwater flow within enlarged subglacial conduits (broad R-channels at atmospheric pressure; Hooke 1989) or ice-walled reentrants with embayments (i.e., geometrically nonuniform conduits) may have effected local northward currents now recorded in sediments toward the western esker flank.

Double-crested ridges, with sediment displacement toward a centre-line depression, were probably initially deposited over ice or ice-rich sediment as single ridges within ice-walled channels. Melting of the underlying ice resulted in a faulted, double-crested ridge (cf. McDonald and Shilts 1975). The rubbly diamicton cap may be a till, which would indicate the existence of an ice roof to the channels. However, it contains very little clay, so may be better explained as the product of marine reworking and solifluction of glaciofluvial sand and gravel, particularly as the exposure is well below marine limit.

The relatively small size of the eskers and double-crested ridges suggests that they were probably some of the last depositional products of the glaciofluvial system. Lack of features indicating former ice-marginal positions, the well-preserved nature of the landform elements, and the variable paleocurrent directions suggest regional ice stagnation toward the end of deglaciation (Sharpe 1992a, 1992b). Therefore, both eskers and double-crested ridges likely represent deposition in ice-walled channels (with or without an ice roof) under stagnant ice conditions.

Inferred sequence of events

Formative processes for the Ferguson Lake glaciofluvial complex have been inferred from landform associations and morphology and sedimentary logs. The event sequence is complicated by the existence of a channel prior to the formation of the streamlined field. This channel was likely cut by earlier channelized subglacial meltwater flow (Fig. 6a). Under high meltwater discharges, localized lifting of the ice from the bed resulted in the deposition of glaciofluvial sediment in a splay-lobe. Beyond this complication, a parsimonious interpretation of the observed landform suite is adopted. A subglacial meltwater sheet is invoked to explain the streamlined forms as surficial elements eroded into thick, ice-rich sediment (Fig. 6b). Such a catastrophic meltwater release may have been accompanied by ice-sheet surging along the path of the meltwater sheet (cf. Shoemaker 1992a). A meltwater-sheet event would have included flow separation and sediment deposition in the obliquely oriented channel. Impingement of vortices on and below the downflow channel wall may have initiated the scalloped margin. Crescentic scours were also eroded at this time, at points of flow reattachment within the tunnel channel. Under waning flow, a reduced meltwater discharge was confined to the tunnel channel, resulting in shallow scours and low residual hills within the channel. It is probable that meltwater also cut upward into the ice at this time, forming a combined R/N-channel (Fig. 6c). When a threshold was reached in the supplying meltwater reservoir, flow within the tunnel channel ceased (cf. Shoemaker 1992b) and ice may have invaded the channel. It is probable that the ice surface gradient was drastically altered by decoupling of the ice sheet from its bed. Later, within stagnant ice, seasonally controlled meltwater drained subglacially by way of an R-channel within the tunnel channel (cf. Shreve 1985). The esker formed in this R-channel (Fig. 6d). Discontinuous eskers within the tunnel channel may be the result of localized conduit closure against obstacles (residual hills), nondeposition, or a downflow connected N- and R-channel meltwater system. Double-crested ridges were deposited in open conduits (Hooke 1989) or cracks (King and Buckley 1969) in stagnant ice (Fig. 6e).

The above sequence is simplified. It is likely that the tunnel channel carried several separate discharge events. In addition,

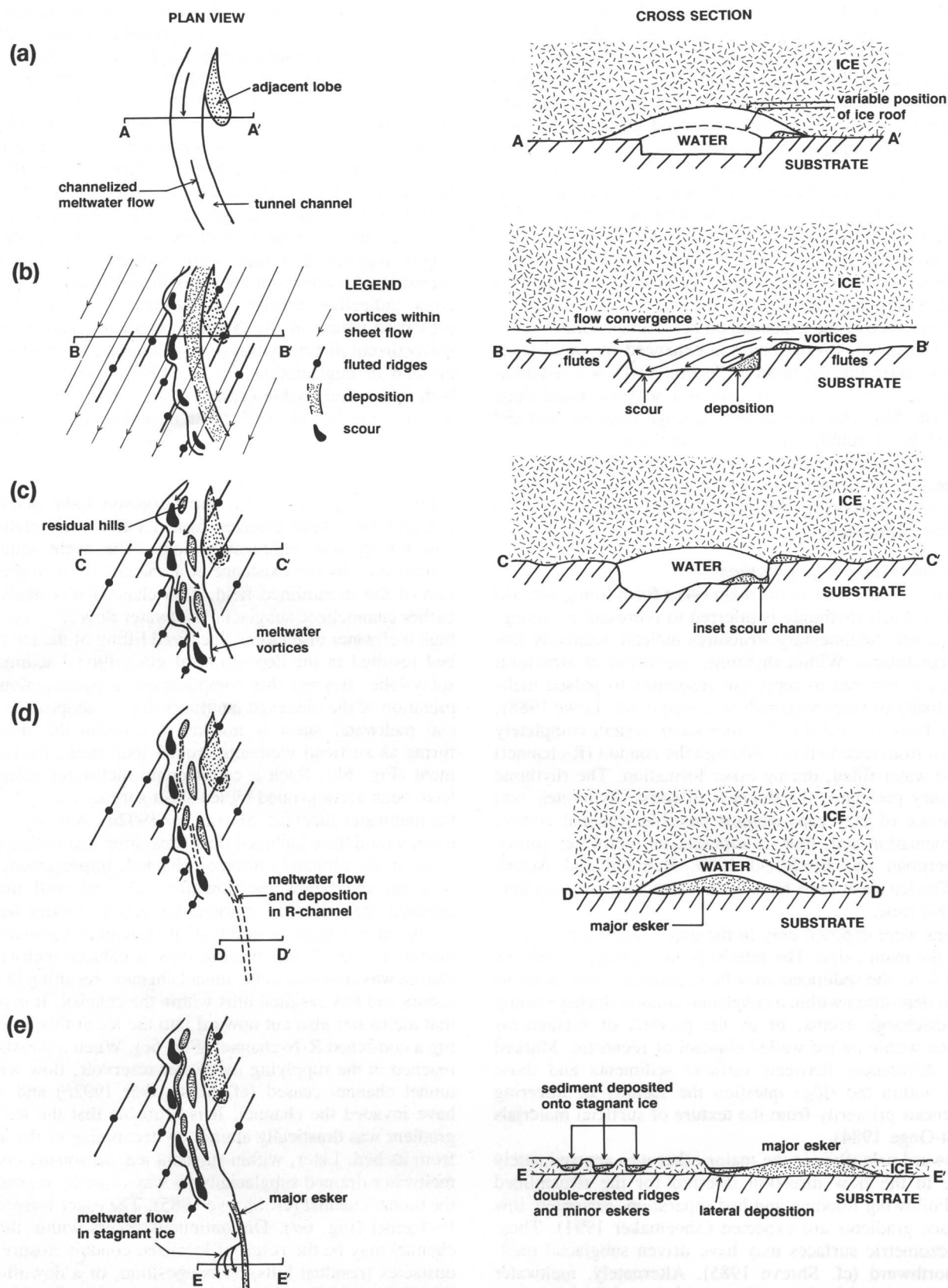


FIG. 6. Schematic illustration of the temporal (a–e) sequence of events at the Ferguson Lake site (note scale changes). (a) Tunnel channel cut into preexisting glacial sediments by earlier catastrophic subglacial meltwater flow in R/N-channel. Overbank deposition of splay lobe. (b) Formation of streamlined terrain, and scalloped margins, crescentic scours, and return eddy deposits of tunnel channel, by catastrophic subglacial meltwater sheet flow. (c) Further erosion of tunnel channel, and formation of shallower scour channels and residual hills, by catastrophic subglacial meltwater flow in R/N-channel. (d) Ice stagnation and formation of major esker by seasonally controlled, subglacial meltwater flow in R-channel. (e) Formation of double-crested ridges and minor eskers in open conduits (presence of ice roof unknown).

meltwater discharge through an R-channel is inferred to fluctuate over time, contingent upon whether supraglacial to subglacial meltwater routing was direct or indirect (cf. Willis et al. 1990). Seasonal influence is suggested by rhythmicity and clay caps in the esker sediments.

Augustus Hills glaciofluvial system

Landform associations

Augustus Hills is part of a broad, flat-topped ridge with an approximate east-southeast–west-northwest trend (Figs. 1 and 7). This ridge is part of a discontinuous glaciofluvial system that may extend from Mount Pelly in the east to about 10 km west-northwest of Augustus Hills, or possibly beyond Wellington Bay (Fig. 1). East of Mount Pelly, a bedrock channel now containing elongate lakes that wrap around residuals, and a field of streamlined forms trending east–west, may also be associated with the ridge (Fig. 1). The channel is inferred to be a tunnel channel. At Augustus Hills, the ridge is up to 3.75 km wide, with a maximum elevation of about 100 m asl (Fig. 7). It exhibits asymmetric cross profiles, an irregular long profile, and a sinuous crest line. The southern portion of the ridge has raised strandlines. The whole feature was drowned by marine incursion to about 157 m asl, after about 9 ka (Sharpe 1992c).

Sedimentary package

Ten recorded sections, ranging in height from 5.00 to 22.74 m, document sediment over about 52 m of the ridge height (Fig. 8). The sedimentary sequence is unknown below approximately 47 m asl at the crest and 34 m asl at the flanks of the ridge. Where exposed, the sediment comprises glaciofluvial sand, silt, and clay, capped in places by shelly deposits and aeolian sand. Lone gravel clasts occur within medium and coarse sand units. Only toward the top of section V007 does gravel constitute the dominant grain size. Here, the cobbles are striated. To the west end of Augustus Hills, isolated boulders are perched on the surface.

Sedimentary architecture is broadly parallel or sheet-like and gently undulatory (Fyles 1963). However, a pronounced undulatory surface is observed towards the top of sections V014 and V015. Section V005, situated on the ridge flank, exhibits faulting, although no one fault extends through the entire section (Fig. 8).

Most sections exhibit a number of fining-upward sequences, from very coarse, coarse, medium, or fine sand to fine sand, silt, or clay. Sedimentary sequences are delimited by event-sequence symbols in Fig. 8. Some sequences coarsen and then fine upward. Sequence thickness varies from about 0.05 to 4.60 m. One sequence in excess of 20 m constitutes most of section V007. Clay caps are generally thin (<0.01 m), but thick clay units (>0.1 m) are observed. Sedimentary sequences may begin with plane-bedded, cross-bedded, or cross-laminated sand, or sand with a poorly defined structure that may be cross-laminated, progress up to cross-laminated sand, sand with a poorly defined structure, or massive sand and silt, and most are draped by parallel-laminated silt or clay. Some cross-bedded cosets in medium sand are abruptly punctuated by clay. In places, tabular cross-beds and RDXL A alternate (section V017, Fig. 8). No oscillatory wave cross-lamination was observed. Paleocurrent measurements from 28 cross-bedded and cross-laminated cosets show a mean direction of 273° (Fig. 8).

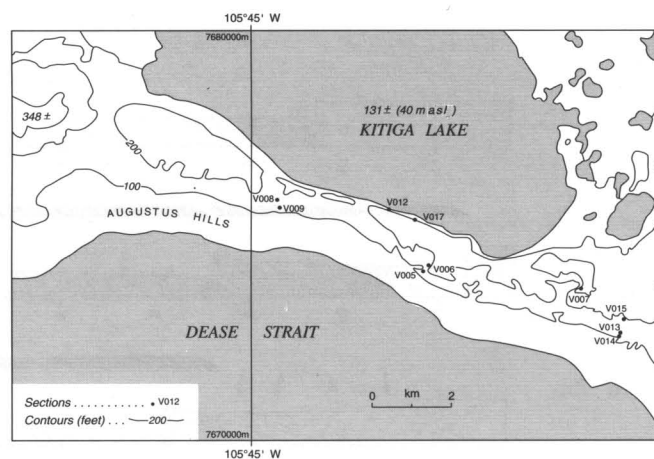


FIG. 7. Map of section locations and morphology at the Augustus Hills site. See Fig. 1 for location.

Most of the contacts between cosets and event sequences at Augustus Hills are sharp and undulatory. However, gradational contacts exist at transitions between RDXL A and RDXL B, or where massive sand and sand with a poorly defined structure repeat. Other contacts are irregular and faulted (cf. section V005; Fig. 8), or loaded, with convolutions and flame structures (cf. section V009; Fig. 8). Loaded contacts are particularly associated with the more massive and texturally differentiated sequences.

Trends in grain size, sedimentary structure, and event-sequence thickness are shown in Fig. 9. It should be noted that (i) section V008 has been omitted, as the sediments in this section appear to have been reworked by marine and aeolian processes; (ii) section V007 has been omitted, as most of the section represents a single event sequence, which is at a higher elevation and noncorrelative with the other sections (this is discussed later); and (iii) section V006 has been omitted from Figs. 9b and 9c, as the sediments have been disturbed by slope movement and exhibit no primary structures. Only sections with more than one recognizable event sequence are included in Fig. 9c. In general, coarse sand is observed only in the more proximal sections, whereas fine sand, silt, and clay accounted for about 70% of the sediment in the more distal sections (Fig. 9a). Trough cross-beds are more frequent proximally and are replaced by tabular cross-beds down-flow. Massive sand dominates the most distal section (Fig. 9b). Syndepositional deformation in the form of flame structures and convolutions is also more prevalent distally. The mean thickness of event sequences decreases distally (Fig. 9c).

Interpretation and discussion

Depositional environment

A sinuous ridge morphology, strong unidirectional flow inferred from sedimentary structures and paleocurrent estimates, and a lack of bidirectional forms, which may have resulted from waves or tidal currents at Augustus Hills, suggest that this ridge is an esker rather than a beach ridge, bay-mouth bar, or spit. The coastal location, strandlines, and presence of marine shells confirm later marine reworking.

As soon as the ice retreated during deglaciation, the isostatically depressed land surface was immediately undated by a postglacial sea. As there was minimal postformational disturbance of the sediments, it is unlikely that they were

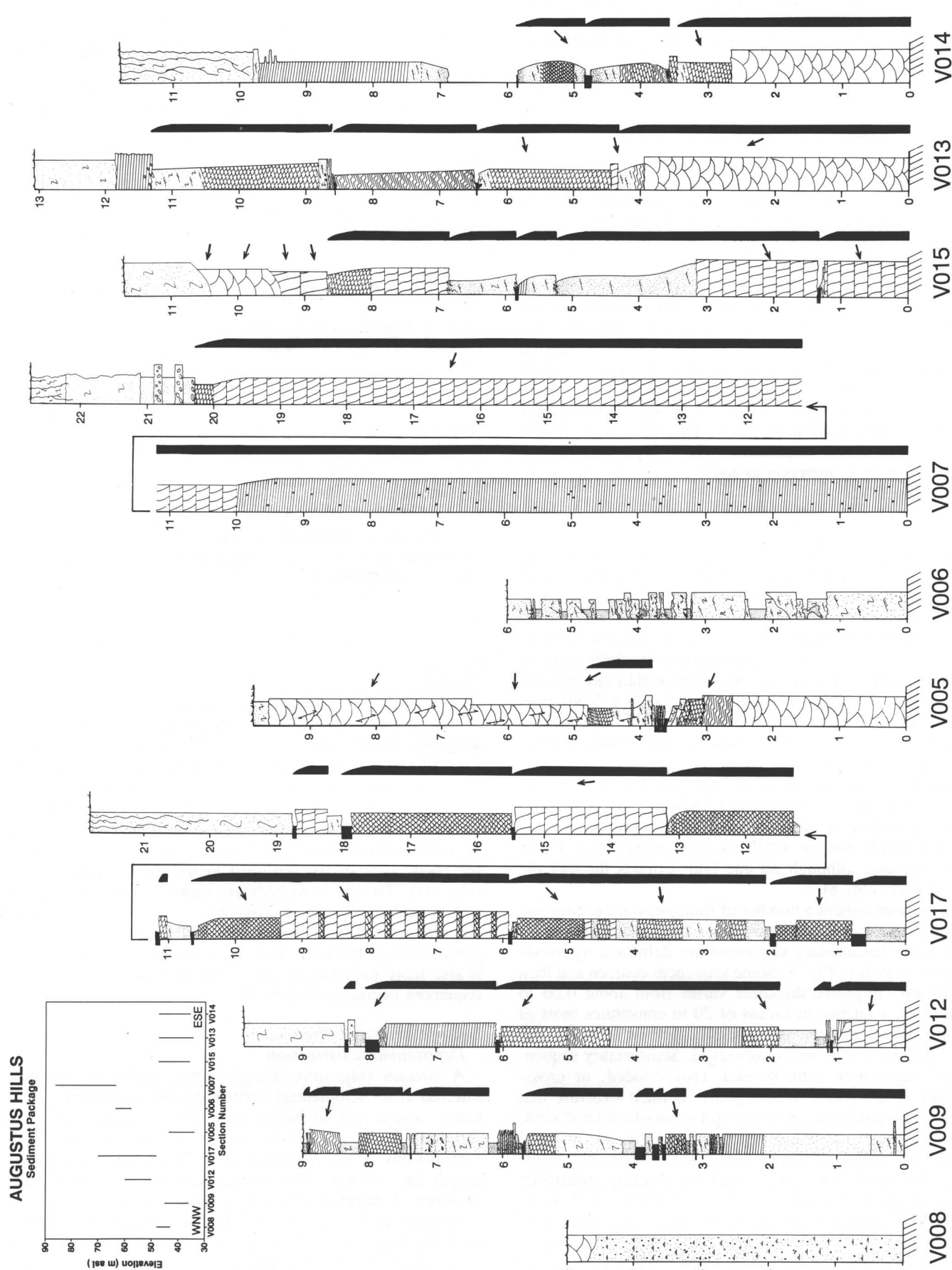


FIG. 8. Sedimentary logs from the Augustus Hills site, with paleocurrent estimates, event-sequence symbols, and elevation above sea level. See Fig. 4 for legend.

deposited onto ice. This rules out supraglacial and englacial sites of deposition (cf. Banerjee and McDonald 1975). Indeed, Powell (1983) has reported that supraglacial streams are absent and englacial streams rarely flow from tidewater glacier fronts because of their highly crevassed nature. The ridge must, therefore, have been deposited subglacially or ice-marginally. In either case, meltwater would have likely debouched subaqueously into high standing water, which was probably brackish.

The sediments are generally similar to subaqueous outwash deposits (e.g., Rust and Romanelli 1975). First, they exhibit proximal to distal fining, which argues for a continuity of sedimentation along the length of the ridge. Second, depositional processes inferred from the frequency of sedimentary structures indicate that deposition from suspension dominated the most distal section. Load structures also indicate high rates of sedimentation from suspension (e.g., Cheel and Rust 1986). It may be expected that RDXL B would be more common than RDXL A in distal locations. This is not the case but may be accounted for by the high frequency of massive units, and units with poorly defined structure, in distal sections. In this case the rate of deposition from suspension is inferred to be so rapid that ripples rarely form in the under-loose bed. Hydrodynamically, the distal transition from trough to tabular cross-beds may be attributed to a reduction in stream power or flow velocity and also implies synchronous sedimentation along the ridge. Third, the mean thickness of event sequences decreases distally.

Subaqueous outwash commonly contains gravel (e.g., Cheel and Rust 1982). Its absence in Augustus Hills has several possible implications. First, the system may have had insufficient velocity or power to entrain and transport gravel. Second, gravel may not have been available to the system. The second possibility seems unlikely, as other smaller eskers in the area and the local till contain gravel. Third, gravel may be present in the ridge core, although it is not exposed. For example, an arched gravel core may exist below 47 m asl at the ridge crest and 34 m asl at the flanks. Surficial gravel units may represent marine winnowed diamicton, which was deposited onto the esker surface from the stagnating ice sheet, or dropstones from icebergs or sea ice.

The irregular crest line is problematic, as deposition into a standing-water body would have produced a surface sloping distally. Some undulatory surfaces within the ridge may have been formed by in-phase waves (Cheel 1991) associated with supercritical density currents (cf. Hand 1974) or supercritical flow exiting a confined system (cf. Rajaratnam and Subramanian 1986). The undulatory character may be a product of time-transgressive sedimentation, or sedimentation into a closed conduit of nonuniform geometry. However, trends in sedimentary texture and structure and a relatively planar sedimentary architecture argue against these interpretations. The irregular ridge surface may be simply a product of post-depositional gullying. From the available exposure it was not possible to determine whether the full sedimentary package (Fig. 8) represents a continuous time (vertical) sequence, or whether vertical and lateral sedimentation were differentiated over time, and related to conduit expansion. Such differentiation in vertical and lateral sedimentation over time may account for the anomalous, noncorrelative, thick (20.3 m) single event, recorded in section V007, close to the ridge crest.

The question remains as to whether the site of deposition was subglacial or ice marginal. The site of deposition must

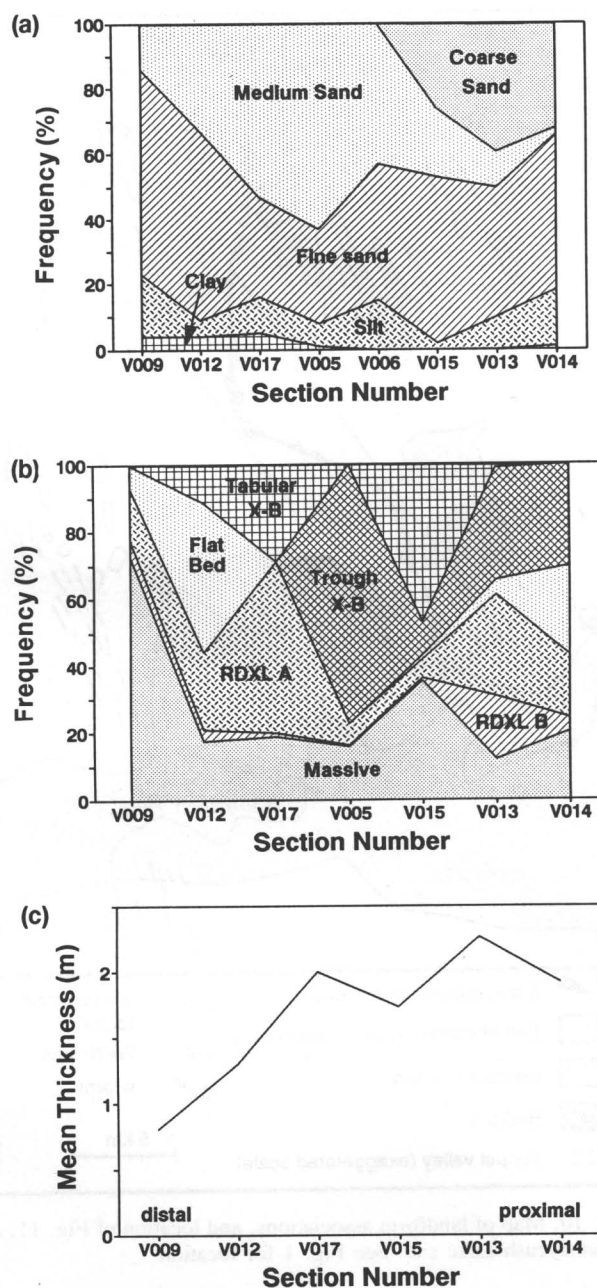


FIG. 9. Augustus Hills. (a) Grain-size frequency by section. (b) Structural frequency by section (flat beds include primarily proximal plane beds and primarily distal draped lamination). (c) Mean event-sequence thickness by section. Sections arranged in order, from proximal (right) to distal. Note sections represent point data, but connecting lines are drawn to aid visual clarity. See text for sections omitted.

account for low paleocurrent variability, ridge morphology, and lateral faulting. Taken together, these lines of evidence suggest that sedimentation must have been in an ice-walled channel (Banerjee and McDonald 1975). There is no diagnostic evidence for or against the presence or absence of an ice roof during deposition of the exposed sediments. However, as Augustus Hills is below marine limit, it is reasonable to assume high sea level at the time of ridge formation. High sea level and lateral ice support favour deposition in a broad ice tunnel flowing full of water. It is difficult to imagine the alternative, a very narrow inlet into the ice front.

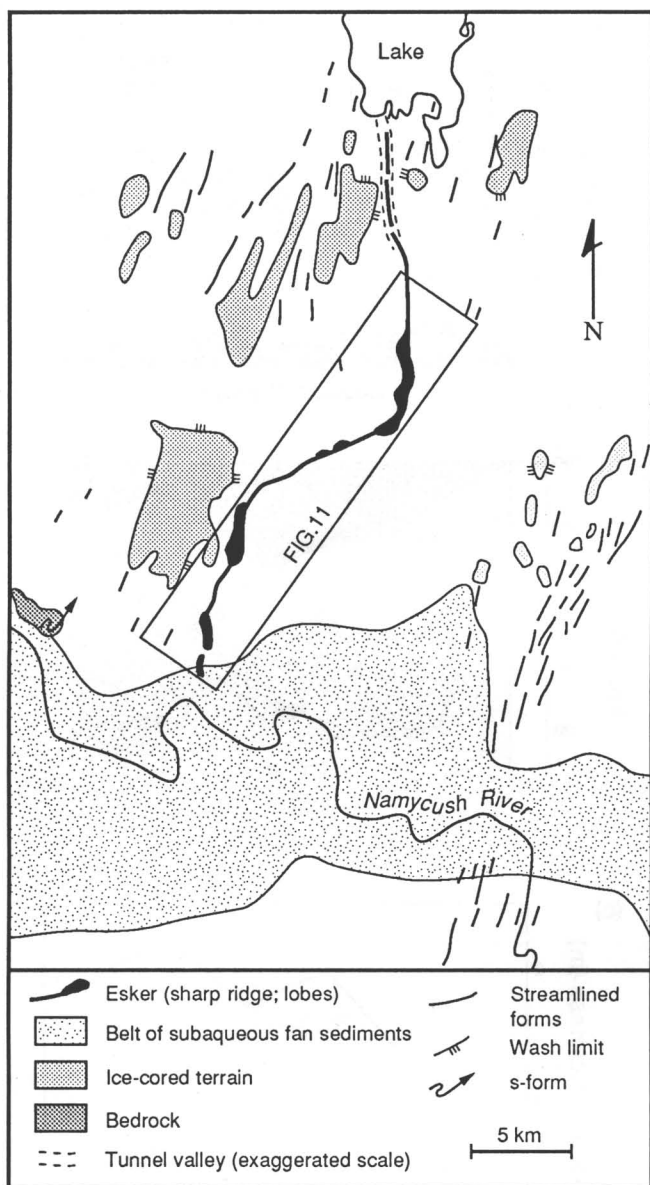


FIG. 10. Map of landform associations, and location of Fig. 11, at the Namaycush Lake site. See Fig. 1 for location.

Meltwater regime

The most significant observation from the exposed sections is sediment rhythmicity. Each of these rhythms may represent one event. The textural and structural progression through each sequence is indicative of waning-flow conditions. Coarsening-to fining-upward sequences are inferred to represent turbidity-current activity. The alternation of ripples and dunes within one event sequence is inferred to record spatial differentiation of sedimentary structures within a declining meltwater discharge sequence, rather than flow-velocity fluctuations. This differentiation may result from ripples climbing up the stoss side of the dunes and supplying sediment to the dune foresets, or to ripples forming in the lee of the dunes before being overridden by dune migration (Allen 1982).

Clay caps were probably produced in standing water when discharge effectively ceased. If meltwater supply was shut down, sea level would have effectively ponded subglacial meltwater by raising the height of the piezometric surface

(Powell 1990), providing an environment suitable for clay deposition. Such shutdown is expected in winter, hence the clay caps are used to infer a seasonality to the rhythmites with relatively thin clay drapes. This implies a supraglacial to subglacial connection in the meltwater system (cf. Hebrand and Ámark 1989) and warm-based ice conditions. Although a seasonal shutdown of meltwater discharge may explain thin clay drapes, it does not account for the relatively great thickness of some of these units (up to 20 cm). In a tidewater setting, salt-water incursion into the conduit during successive winters may have flocculated clays. Thick clay units may have resulted where clay was continuously supplied by low meltwater discharges near the end of the melt season and was flocculated upon contact with salt water.

In addition to the seasonal implications of clay caps, many of the event sequences are suggestive of quasi-continuous or episodic sedimentation from turbidity currents (cf. Burbidge and Rust 1988). Conversely, the presence of persistent plane-bedded and cross-bedded units is indicative of more steady, uniform flows. Alternatively, these units may indicate very high energy turbidity currents with power to transport coarse sands and deposit them as traction bedforms (Allen 1982). Diurnal or weather related discharge events affecting subglacial water pressure and subglacial plumbing may have controlled these sediment pulses (Østrem 1975; Willis et al. 1990).

To summarize, Augustus Hills is inferred to have formed subaqueously by deposition in an ice-walled channel, probably with an ice roof, in stagnant ice. Closed-conduit conditions are probable if high sea levels are assumed. The sedimentation is rhythmic and was probably seasonally controlled. Pulses within seasonal events may be the result of diurnal or weather-related discharge events, or changes in subglacial plumbing (Gorrell and Shaw 1991). The disturbed sand at the top of most of the sections is the product of later ridge modification by marine, mass-movement, periglacial, pedogenic, and aeolian activity.

Namaycush Lake glaciofluvial complex

Landform associations and ridge morphology

Namaycush Lake glaciofluvial complex provides an example of the association between an esker, subaqueous fans, and extended deposits, located at the edge of streamlined terrain, and extending from a channel to the north (Figs. 1, 10, and 11). Extended deposits are defined as a band of hummocky sediments that occur lateral to, and run parallel to, a bend in the esker ridge. Adjacent streamlined terrain, escarpment noses, and comma forms indicate flow from the south-southwest, whereas streamlined terrain to the north indicates divergent flow from the northeast (Fig. 1). Ice-cored hills are present within streamlined terrain (e.g., Sharpe 1992a). A broad belt of subaqueous fan sediments occurs to the south (Fig. 10). The esker is continuous for about 27 km and trends south and southwest across relatively flat terrain, below marine limit. It is a single, sharp-crested, sinuous ridge, with no sedimentary exposures (Fig. 11). Three lobate fans extend from the esker (1, 2, and 3, Fig. 11). In addition, extended deposits appear to underlie the main ridge at site 4 (Fig. 11).

Sedimentary sequences in fans: observations

Two sedimentary logs were recorded for fans 1 and 3 (Figs. 11 and 12). Paleocurrents from RDXL indicate paleoflow with a southward component (130–220°; Fig. 12). Fan

1, the smallest fan, contains silt to coarse sand, with fine sand the most common (section V033; Fig. 12). A number of fining-upward event sequences, varying in thickness from 1.50 to 0.02 m, are observed. RDXL A dominates the lower 6 m of the section, whereas massive and plane-bedded sand appear to dominate the upper part. No clay is present.

Fan 3 contains sediments with a maximum grain size of medium-fine sand (section V034; Fig. 12). In detail, the recorded succession comprises a large number of fining-upward packages in massive sand and silt, with thicknesses varying from a few millimetres to a few centimetres. Only two clay bands a few millimetres thick were observed.

Fans and extended deposits: interpretation

The sedimentary package in fan 1 (section V033) indicates pulsed flows with traction processes having dominated the lower 6 m of the section, and sedimentation from traction and suspension having dominated the upper part. If clay drapes are interpreted as seasonal markers, their absence in fan 1 suggests that the whole sequence was deposited in a single year (Smith and Ashley 1985). Given the small size of the fan, this suggestion is plausible.

Deposition from suspension with very little traction transport may be inferred from fan 3 sediments. Thin clay bands imply seasonal control on sedimentation, and deposition of section V034 over 3 years is favoured. The event sequences between these clay bands have a much higher frequency than those observed in the Augustus Hills esker. Diurnal or weather-related controls, or changes in subglacial plumbing related to fluctuations in subglacial water pressure within a melt season, may be inferred for these pulses. The record of numerous within-season pulses suggests that fans preserve low-magnitude events better than do eskers (cf. Gorrell and Shaw 1991).

The location of the extended deposits at a bend in the esker path may be critical to their interpretation. When water flows around a bend, a relatively high pressure is created. During high meltwater discharges this could cause localized hydraulic lifting. An increase in meltwater discharge causes an increased velocity within a conduit, which results in increased sediment transport. Local uplift at the bend causes local flow expansion and deposition of extended deposits. When discharge declines, normal high-pressure zones are reestablished at the conduit margins, isolating subsequent esker deposits from the extended deposits. The localized ice floatation inferred here may require proximity to a grounding line (cf. Gorrell and Shaw 1991), or to an ice margin that may be represented by the belt of subaqueous fan sediments.

Discussion: depositional environment and meltwater regime

The association of a continuous esker ridge with a possible tunnel channel to the north, and a broad belt of subaqueous fan sediments to the south, suggests a subglacial site of deposition for the esker ridge at the Namaycush Lake site. The thick belt of subaqueous fan sediment to the south suggests that fan 1 may record an ice-marginal position (cf. Burbidge and Rust

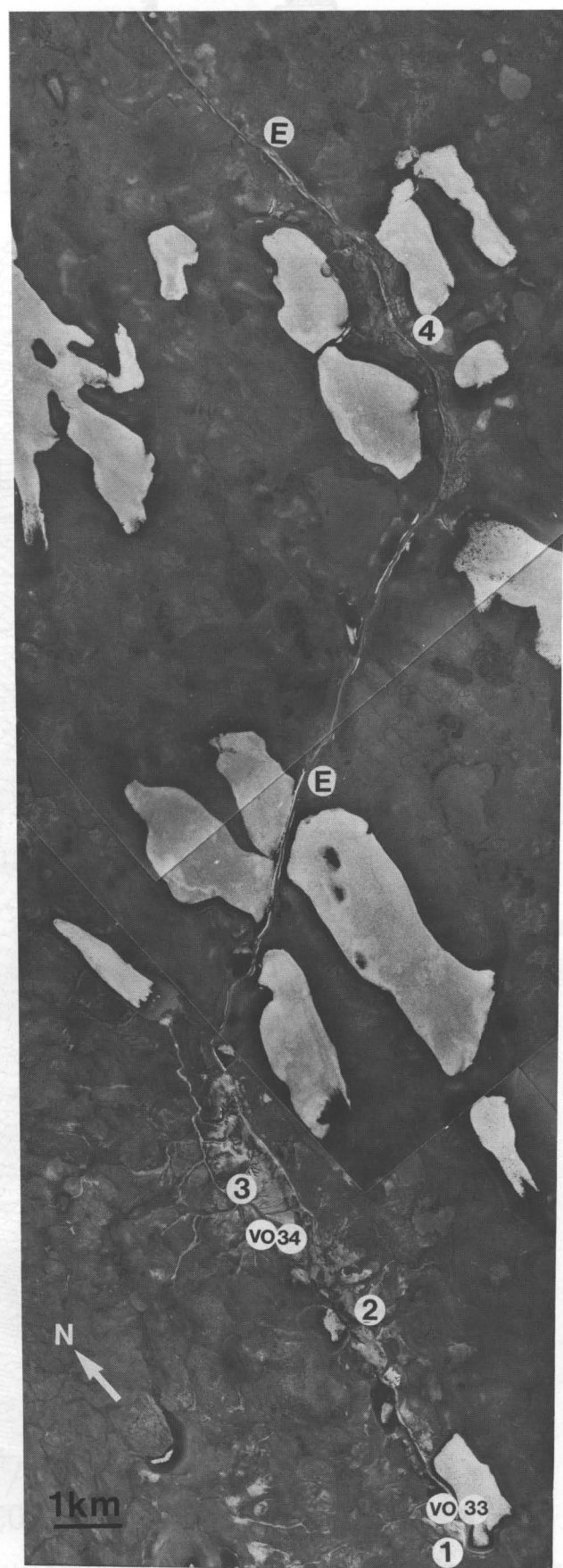


FIG. 11. Air photograph mosaic showing esker (E), fans (1–3), extended deposits (4), and section locations (V033, V034), at the Namaycush Lake site. See Fig. 10 for location. Air photographs A16170-49, A16170-109, and A16170-110 ©16 July 1958 Her Majesty the Queen in Right of Canada reproduced from the collection of the National Air Photo Library, with permission of Energy, Mines and Resources Canada.

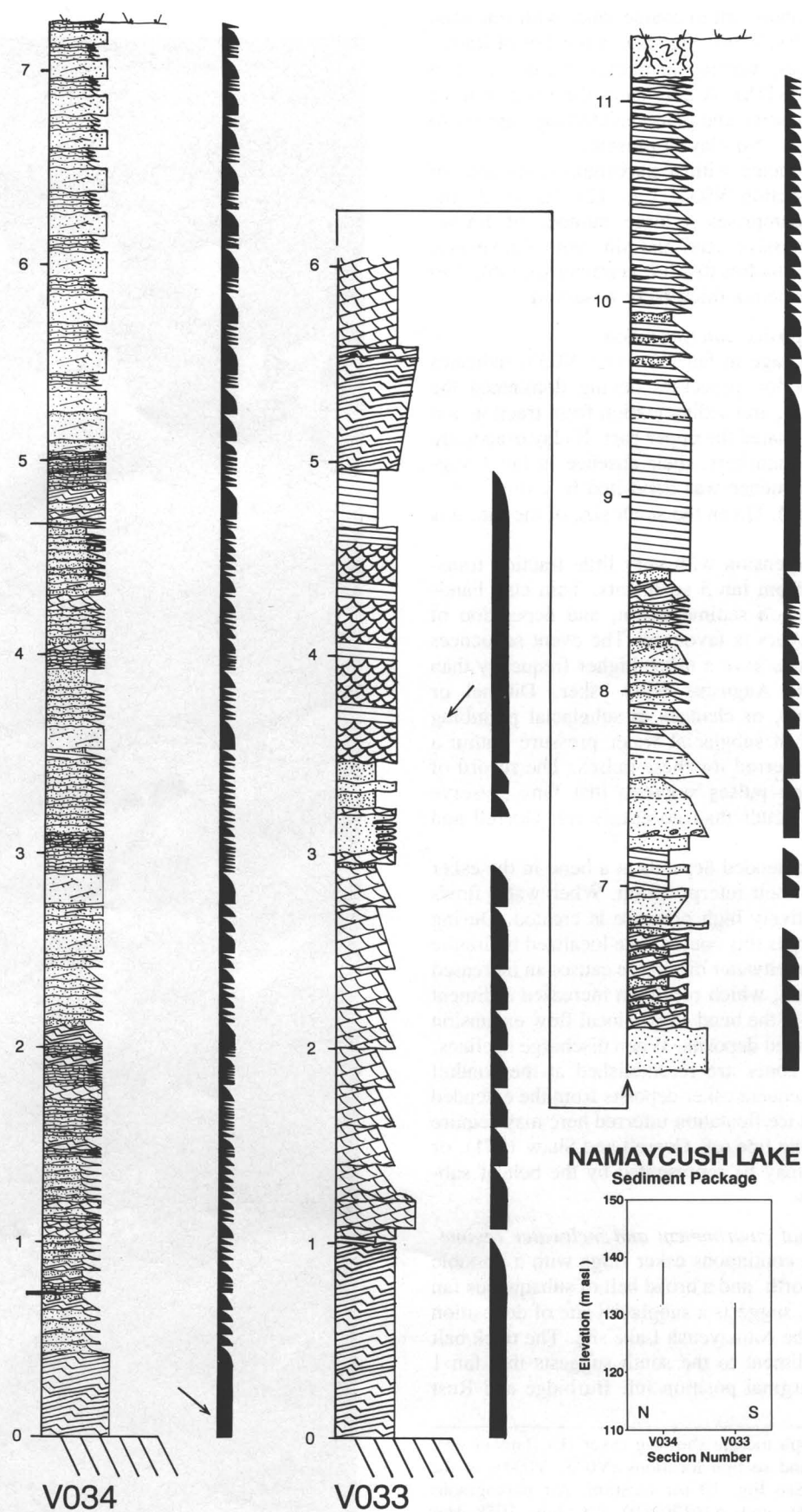


FIG. 12. Sedimentary logs from the Namaycush Lake site with paleocurrent estimates, event-sequence symbols, and elevation above sea level. See Fig. 4 for legend.

1988). However, the lack of other east–west belts of subaqueous sediments, and the landform associations at site 4, argue for subglacial deposition in cavities, perhaps proximal to a grounding line (cf. Gorrell and Shaw 1991) for the remainder of the fans.

Paleoflow patterns present an enigma in event reconstruction at the Namaycush Lake site. Whereas the esker sediments indicate a southerly paleoflow, adjacent streamlined forms indicate earlier northeasterly flow. If streamlined forms, comma scours, and escarpment noses relate to erosive meltwater sheet flows (cf. Shaw et al. 1989), such exceptional drainage events would have lowered ice-sheet profiles and may have influenced local distribution of meltwater head, or both, producing a new hydraulic gradient to drive subglacial meltwater in the opposite direction. The time between the formation of the streamlined fields and the eskers is unknown. It is possible that the esker was formed by meltwater that was driven by a hydraulic gradient inherited from the event which produced the streamlined field to the north.

Esker deposits are inferred to record subglacial drainage of meltwater from supraglacial sources. However, the seasonal melt control on esker sedimentation may be either by direct supraglacial to subglacial routing or by indirect filtering through a subglacial meltwater system, which may also include linked-cavity or cavity-film drainage (cf. Willis et al. 1990).

Implications for ice-sheet dynamics

Reconstruction of ice-sheet dynamics from landforms requires interpretation of the sediments within them as well as of their morphology and landform associations. The details and vagaries of glacial hydrology and hydraulics for three sites on Victoria Island have been outlined. In general, the landforms produced by erosional events (streamlined forms and tunnel channels) are inferred to record low-frequency, high-magnitude changes in meltwater discharge related to catastrophic drainage sheets and combined R/N-channels, whereas depositional landforms (eskers, associated fans, and extended deposits) record the subtleties of lower magnitude, R-channel drainage of predominantly supraglacial meltwater. Together, these landforms record the activity of subglacial meltwater processes through the course of deglaciation. A temporal disconnection between the different drainage conditions is suggested by possible paleoflow reversals, between the formation of the streamlined terrain and eskers. Late-glacial meltwater storage and flow may have locally altered the low ice-sheet profile (Shoemaker 1991, 1992a, 1992b) to produce cross-cutting relationships and even flow reversals between streamlined forms and eskers.

It has been suggested that the eskers at the three sites lack major post-depositional disturbance and have in common a tunnel channel. Consequently, at least an early phase of esker sedimentation may have occurred in a subglacial environment. Although it is not possible to unequivocally determine whether the eskers were formed contemporaneously along their length, or in segments, time-transgressively, textural and structural trends in sediments suggest a continuity of processes along their length. This continuity argues for synchronous sedimentation along the length of the esker ridges, in subglacial conduits, rather than time-transgressive sedimentation at a retreating ice margin. This is supported by a lack of recessional ice-marginal landforms and sediments (Sharpe 1992a).

The details of esker sedimentology and morphology have

been used to reconstruct local ice-sheet dynamics. The presence of eskers indicates warm-based or polythermal ice conditions. A continuous esker at the Namaycush Lake site records seasonally controlled discharges with localized ice floatation events in a subglacial conduit near a grounding line. The less connected or disconnected ridges at Augustus Hills and Ferguson Lake sites also record seasonally controlled discharge events and were produced by a thinning and stagnating ice mass. They may have been deposited in subglacial R-channels or ice-walled reentrants, the former being more probable.

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