NATURE OF ESKER SEDIMENTATION[1]

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ABSTRACT

Broad questions of esker sedimentation are reviewed in this paper. Two main environmental factors, nature of the conduit through which the esker stream flowed, and site of deposition, control esker sedimentation and commonly can be determined from the sedimentary succession. Interaction of these two factors permits definition of three different models of esker sedimentation: *open-channel, tunnel* and *deltaic*. Morphology of the esker ridge, sedimentary structures, facies relationships and paleocurrent variability are important parameters of proposed sedimentation models. The models are discussed on the basis of field data from eskers at Peterborough, Ontario and at Windsor, Quebec.

Sediments of the Peterborough esker were deposited largely in an *open channel* bordered laterally by ice walls. Backset beds related to antidunes are preserved at places. A common environment was *deltaic*, where dunes and ripples delivered sediment to avalanche faces; progressively downstream from the large foresets were regressive, sinusoidal, and progressive ripples, respectively. These in turn pass into graded beds and then into lacustrine rhythmites.

Tunnel sedimentation is illustrated by sediments in single steep-sided ridges in the Windsor esker. Sheet-like cross-bedded and parallel-bedded gravel and sand units persist downstream without facies change and are arranged in vertically stacked cycles that may be annual. Flow depth in the tunnel was 1 to 4 m and accumulation of sediment was accommodated by a melting upward of the ice roof.

Deltaic sedimentation is illustrated by beads in the Windsor esker that were deposited annually as subaqueous fans in the water body at the mouth of the subglacial tunnel. Cobble and pebble gravel at the proximal end of the bead intertongues over a few meters in a downstream direction with ripple-laminated fine sand, units of "structureless" fine and medium sand, and graded beds.

INTRODUCTION

An esker is a linear accumulation of gravelly and/or sandy stratified sediment that was deposited by a stream confined on both sides by glacier ice. In some cases, though not necessarily, the stream was also confined on the top and/or bottom by glacier ice.

Studies of eskers are numerous and have had a number of objectives. Most have been concerned with interpretation of late-glacial environments (*see* Boulton, 1972, and Flint, 1971, for many references). Others have studied the use of eskers as a drift prospecting medium (Cachau-Herreillat and LaSalle, 1971; Hellaakoski, 1931; Gillberg, 1968; Lee, 1965, 1968; Shilts, 1973), as a source of groundwater (De Geer, 1968; Parsons, 1970), and as a source of more fundamental data on fluvial sedimentary processes (Aario, 1971, 1972a and b; Allen, 1971); Shaw (1972) contributed a useful paper on the distributions of sedimentary facies in three glaciofluvial deposits in England. Eskers have only rarely been diagnosed in the bedrock record (Frakes and others, 1968).

The present study reviews briefly some characteristics of eskers that must be explained by any comprehensive theory of esker formation. These are based partly on literature review and partly on field study by McDonald of eskers in the District of Keewatin, northern Canada. The principal theories of esker formation are reviewed in terms of their sedimentary implications. Sedimentary structures and facies relationships in two eskers formed during late Wisconsinan deglaciation at Peterborough, Ontario, and at Windsor, Quebec have been studied in detail by the present authors, and these data are used to construct models of esker sedimentation.

CHARACTERISTICS OF ESKERS

Distribution

Eskers occur only in areas that have been glaciated. In North America they occur mostly south of about 72°N, suggesting that wet-based, or temperate, glaciers provide more favorable hydrological conditions for esker formation than do glaciers frozen to their bases.

Although isolated eskers are common, eskers tend to occur in swarms such as those in Scandinavia, Maine, Labrador, and the District of Keewatin. These are areas where large remnant Pleistocene ice sheets wasted away, and it seems probable that the esker swarms simply reflect widespread and rapid ablation having produced an abundant supply of meltwater within the glacier. Eskers in such

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swarms are commonly linked into networks in which the overall network pattern is parallel, a result of steep hydraulic gradients near the glacier termini having been oriented parallel to the surface slope of the glacier. Seldom, if ever, are more than two orders of tributaries (in the sense of Horton, 1945) linked to a trunk esker. In the District of Keewatin, eskers in swarms trend roughly parallel to each other and are regularly spaced about 13 to 14 km apart. This spacing, evidence of a well integrated meltwater escape system in the glacier, would be a function of the hydraulic conductivity within the glacier, the discharge required to maintain the channel against any tendency of the ice to close it, and the distance back from the glacier terminus over which the water collection system was integrated.

Eskers emerging from present-day glaciers have been reported by many workers (for example, Hartshorn, 1952; Howarth, 1971; Ives, 1967; Jewtuchowicz, 1965; Lewis, 1949; Meier, 1951; and Price, 1966, 1969). The glaciers are commonly valley glaciers, the eskers tend to be small, and ice cores make up a large proportion of the ridge volumes. The large Pleistocene continental ice sheets that formed the major esker systems of the world were hydrologically of such a larger scale than small glaciers existing today that it is debatable to what degree modern subaerially exposed eskers should constrain the interpretation of sedimentary sequences in the large "fossil" eskers. In addition, it is clear that many of the large Pleistocene eskers formed beneath ice sheets whose termini rested in deep bodies of standing water, a situation where it is difficult to study modern analogues.

Esker Morphology

Morphologic characteristics, insofar as they can be related to a particular sedimentation history, must be considered in a study of the environments of esker deposition. Eskers may occur in association with other sedimentary and morphologic features that are closely related, both in location and origin, to the processes of esker formation. The entire "esker complex," then, includes the esker itself along with such features as marginal troughs, kettles, kames, and esker deltas.

Basic morphologic types of eskers are summarized in Table 1. The common morphological expression of an esker is that of a single, long, relatively narrow, sinuous ridge. The ridges may be sharp crested or flat topped. The single-ridge types, however, may be straight for long distances, while in other cases they seem to be truly meandering. The term "beaded esker" is applied to those reaches of eskers that consist of a series of separate, regularly spaced, roughly conical hills or "beads" of esker sediment. The beads are commonly 100 to 200 m diameter and 5 to 15 m high. Alignment of the beads forms an easily recognizable esker trend. Although occasionally successive beads are in contact with each other, more commonly they are separated by lower terrain underlain by till or by lacustrine or marine sand.

TABLE 1.—MORPHOLOGIC VARIATION IN ESKERS

Basic morphology	Characteristics of esker complex	Deglaciation environment
1. Continuous single ridge; flanking outwash	Central esker ridge is highest element of complex; flanked progressively outward on each side by elongate marginal kettles, outwash terraces, and scalloped till plain; abrupt topographic discontinuities.	No standing water at glacier terminus.
2. Continuous single ridge; no flanking outwash	Ridge subdued by subsequent wave action commonly resulting in beach development on esker ridge; flanked by till.	Deposited within glacier but below level of standing water body at glacier terminus.
3. Broad ridge with multiple crests	May or may not be flanked by outwash; commonly multiple ridges form reticulate pattern.	Where broader than 200 to 300 m, probably in part subaerial and some may be part of interlobate moraine complex; narrower varieties flanked by outwash indicate no standing water at glacier terminus.
4. Beaded	Pronounced isolated beads are regularly spaced and flanked by till.	Deposited where esker stream entered standing water at glacier terminus.

Morphologic variations are common along a single esker, especially between types 2 and 4 (table 1). Most long esker ridges have gaps in them that could result either from nondeposition or from postdepositional erosion. Postdepositional processes such as beach formation accompanying shallowing of the standing water body, solifluction, slumping, frost-cracking, and eolian activity commonly modify and subdue the original morphology and rework the surface sediments.

Dimensions of eskers can be summarized as follows: (a) *Height*—rarely more than 50 m but have been recorded to 80 m (Donner, 1965); (b) *Thickness of gravel*—225 m of esker gravel have been drilled in the Munro esker of northern Ontario although the esker stands only 30 m above surrounding terrain (Hobson and Lee, 1967); (c) *Width*—can be as large as 7 km for the broad flat-topped Munro esker complex, although generally widths of esker ridges are less than 150 m; (d) *Length*—variable from a few hundred meters to over 800 km, including gaps, for the Thelon esker extending westward from Dubawnt Lake in the District of Keewatin (Craig, 1964).

THEORIES OF ORIGIN AND IMPLICATIONS FOR SEDIMENTATION

Beyond the general acceptance of eskers as ice-contact glaciofluvial features, little consensus exists with respect to theories of origin. In view of observations of modern eskers and variation in morphologic and sedimentologic types in Pleistocene eskers, it seems certain that environments of esker deposition varied considerably in detail.

Most theories can be grouped according to their principal concern: (a) *Formation and maintenance of the conduit*—the process by which meltwater was localized in specific channels; (b) *Position of esker sediments with respect to the glacier*—whether the esker stream occupied a subglacial, englacial, or supraglacial position; (c) *Nature of the conduit*—whether the esker stream flowed in an open channel or in a tunnel flowing full; and (d) *Site of deposition*—whether deposition took place inside the conduit before reaching the glacier terminus, or at the glacier terminus where flow conditions probably changed radically.

Formation and Maintenance of the Conduit

A few proposals have been made regarding the process by which conduits for meltwater originated and were maintained. Carey and Ahmad (1961) suggested that the water seepage pressure gradient in the saturated till at the base of a glacier may have been sufficient near the terminus to open a conduit in the till by piping. Once formed, this conduit would be maintained and enlarged by erosion and could form a subglacial tunnel localizing esker formation.

In Finland, Hyyppä (1954) and Härme (1961) have related esker trends to fault lines. They proposed that reactivation of old faults, perhaps accompanying isostatic rebound, resulted in lines of weakness in the glacier that then became loci for meltwater flow. It is possible, however, that fault lines are coincident with valleys and that the basic control on esker location is topographic.

Two important papers have recently discussed the flow of water within glaciers (Röthlisberger, 1972, and Shreve, 1972). Röthlisberger showed that: (a) subglacial water migrates down pressure gradients toward main flow arteries where velocity is greater. Addition of this water results in further concentration of water in main arteries; (b) a conduit will rapidly (days) increase its diameter in response to increased seasonal discharge, but closure of the conduit due to creep of ice during seasonally low discharge has a much longer time constant (months or years); and (c) a conduit may be straight, meandering, or even 'braided' depending upon the hydraulic gradient. Shreve (1972) argued that: (a) the stable mode of subglacial water movement is in tunnels; and (b) subglacial formation of eskers is favored by large discharge (i.e. widespread ablation) and low glacier-surface gradient.

Position of Esker Sediments with Respect to the Glacier

Subglacial, englacial, and supraglacial locations of esker streams have all been reported from modern environments. It is also probable that some eskers started to accumulate in tunnels and, after thinning and collapse of the ice roof, final sedimentation took place subaerially. Criteria that could be applied to determination of the position of the esker sediments with respect to the glacier include:

(a) *Bedrock valleys*—In some cases, drilling and seismic data indicate that eskers are located along the axes of buried bedrock valleys (Hobson and Lee, 1967; Hobson and Maxwell, 1968). Elsewhere bedrock surfaces, on which the eskers directly lie, have been scoured free of till for several tens of meters on either side of the esker ridge. In these situations it seems clear that the esker stream flowed at the base of the glacier and that erosion by water contributed sediment to the esker stream.

(b) *Basal till overlying esker sediment*—Where a basal till occurs at the highest stratigraphic level in an esker and where it can be shown that the till belongs to the same glacial episode as the esker, it is evident that the esker formed in an englacial or subglacial position;

(c) *Deformed sequences*—If deformation of an entire sequence can be related to an underlying ice mass that formed an integral part of the glacier (see McDonald and Shilts, this vol.), then that portion of the esker initially would have occupied either an englacial or supraglacial position. Price (1966, p. 123) has reported good evidence to show that as ice melts out from beneath esker gravel ridges, a ridge form can be preserved. The present authors, however, concur with Price that it is difficult to conceive of a sedimentary sequence being let down an appreciable distance, as underlying ice melted, without intense disruption of primary sedimentary structures; and

(d) *Diapiric intrusion*—In two eskers from southeastern Quebec diapirs of glacial-lake silt and clay have been extruded vertically upward several meters into the esker cores (fig. 1). The diapirs are tabular and can be traced for several tens of meters parallel to the esker axis. The primary laminations are vertical. The diapirs have been interpreted as the result of differential downward pressure exerted by the weight of the ice along the flanks of the eskers, causing lateral flow of the plastic clays and their extrusion upward into the conduit. Such esker streams were evidently flowing at the base of a glacier that had advanced over varved sediment.

Nature of the Conduit

Stream sediments have been observed in channels with and without ice roofs in modern glaciers. Hydraulically, a tunnel not flowing full is simply an open channel. We will consider a "tunnel," therefore, to refer to a closed conduit flowing full, and an open channel to be distinguished by a free upper surface having air in contact with the water.

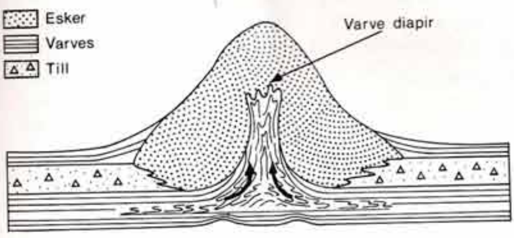


FIG. 1.—Diapiric intrusion of varved silt and clay upward into core of esker.

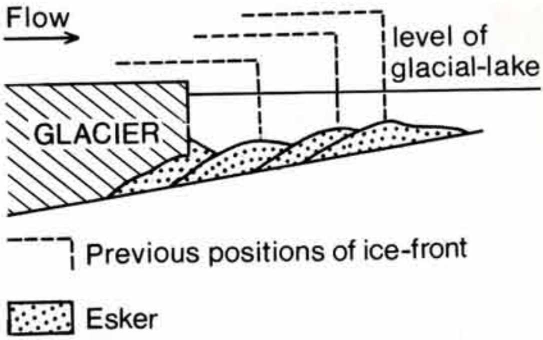


FIG. 2.—Deposition of esker sediment as a time-transgressive series of subaqueous fans not requiring subglacial flow up an adverse slope.

The observation that many eskers increase in altitude downstream, at least locally, led early workers to the hypothesis that flow in a tunnel under a hydrostatic head permitted the esker stream to flow up an adverse slope. Two assumptions underlie this hypothesis, both of which are subject to testing in the sedimentary sequence: (a) that the sediments were not deposited over ice and subsequently let down as the ice melted; such a lowering of the sediment pile would produce intense deformation in the sequence; and (b) that the esker is not significantly time transgressive, that is, that the sediments were not deposited at progressively later times in an upstream direction (fig. 2); this could be verified by detailed facies studies. Figure 2 depicts a series of subaqueous fans formed at the mouth of the channel (whether open, or a tunnel). When a number of such fans are built at the terminus of a retreating ice front they may be shingled on top of one another forming a time-transgressive linear ridge that rises, but is progressively older, in a downstream direction.

Lateral facies relationships that indicate overbank flooding from a central channel (Saunderson and Jopling, 1970; Shaw, 1972, p. 34) would support an open-channel flow model, as would the occurrence of such subaerial features as mud cracks. A greater abundance of silty clay lenses could be the product of frequent avulsion of subaerial channels resulting in backwater areas in which fines could settle.

Shaw (1972) concluded that three eskers in

FIG. 3.—Backset bedding 1.5 m thick in Peterborough esker (locality 14, fig. 20). Flow direction was from right to left as indicated by underlying ripple-laminated sand, several paleocurrent measurements in other facies at this site, and its orientation with respect to the esker trend. Shovel is 50 cm long. (GSC 202287-A).

England had been deposited in open channels. He based his conclusions principally on the fact that a lateral fining of the fluvial sediment occurred about a central coarse zone. He observed that in contrast to nonglacial fluvial models, the vertical sequence indicated little lateral migration of the main channel, a fact that he attributed to low sinuosity of the esker streams. However, the occurrence of faults adjacent to the central coarse zone raises the possibility that the eskers have a complex origin, perhaps originating in subglacial tunnels that, after collapse or melting of the roof, had a final open-channel phase.

Sedimentary structures can complement other lines of evidence to distinguish tunnel from open-channel environments. Subglacial tunnels flowing full are gigantic natural pipes in which bed forms that depend on surface water waves cannot be stable. Such free-surface waves are necessary for the formation of antidunes (Kennedy, 1963), so the formation of antidune bedding would require an open channel. An exception could be made in the case of a density underflow that could sustain waves at the interface between the two fluids; it would be necessary to draw the distinction on the basis of sedimentary structures and facies relationships. In two localities in the Peterborough esker, for example, cross beds 1 to 2 m thick occur in gravelly coarse sand and dip consistently in a direction opposite to the general current flow (fig. 3). These have been interpreted as backset beds associated with antidunes and, by inference, with open-channel flow.

Experimental study of bed forms and sedimentary structures in pipes flowing full and up an adverse slope indicate that, as bed shear stress is increased over a sand bed, ripples give way to dunes, then to a plane bed, and then erosion of the entire bed results in sediment being transported in a heterogeneous suspension (McDonald and Vincent, 1972). An antidune bed mode was not observed. Dune height was observed to be ⅓ to 1 times the hydraulic mean depth (cross-sectional flow area/wetted perimeter). Thus it seems possible to use dune height as a guide to water depth in pipe-flow systems, just as has been suggested for open channels (Allen, 1963). McDonald and Vincent (1972, p. 21) show that without making too serious assumptions regarding how much of an idealized cross-section is filled with sediment, or regarding the position of an observation with respect to the highest point in a circular-shaped roof, actual water depth would be 2 to 3 times the hydraulic mean depth. Thus, as a guide, actual water depth would be about 2 to 10 times dune height. Deposition in a tunnel could be inferred by calculation of a stream-flow depth that would indicate a stream surface significantly below that of an ambient water level imposed by an associated glacial lake.

Site of Deposition

Sediment-laden water flowing through a conduit in a glacier can deposit sediment: (a) far back within the conduit; (b) subaqueously, that is, into a standing water body at the ice front; or (c) subaerially at the glacier terminus. Without respect to whether flow occurred in an open channel or in a tunnel, some conclusions regarding the site of deposition can be made from examination of the sediments.

Deposits within the conduit are supported laterally by the glacier. As the glacier melts, these supports are removed and the flanks of the esker collapse to a stable angle of repose (McDonald and Shilts, this vol.). This abrupt side topography with internal evidence of failure, characteristic of most eskers, is evidence that deposition took place in the conduit. The occurrence of flowtill or exceptionally large blocks in the esker sequence also may result from the presence of glacier ice along the flanks of the esker stream. Sediment facies should be relatively persistent in longitudinal section.

Eskers can also be deposited right at the ice front where they owe their linear-ridge form to progressive retreat of the ice front and to the esker stream having been laterally constrained by glacier walls just upstream from the terminus. Discharge of the esker stream into a standing body of water would result in sudden decrease of competence with deposition of most of the sediment load just beyond the ice front. The sides of this deposit initially would be at a relatively stable angle and post-depositional collapse features would not be expected there. In transverse section, bedding surfaces should be roughly parallel to the topographic surface. From proximal to distal location in longitudinal section, the sediments rapidly should become finer grained, reflecting the rapid decrease of competence.

Subaerial discharge at the ice front would involve only removal of the constraining walls. Flow would expand into a conventional outwash stream system, the 'esker' having been reduced simply to the highest point in the cross-profile of the outwash train. This point might also be marked by deposition of coarser components of the sediment load due to reduction of bed shear stress as flow expanded and shallowed at the terminus.

Nature of the conduit and sites of deposition can be combined into various environmental types of eskers as illustrated in Figure 4. It is apparent from the figure that there are three basic situations in esker sedimentation. When deposition takes place within the conduit the environment can either be (1) an open channel, or (2) a tunnel. When deposition takes place subaqueously at ice front the environment is (3) a delta, irrespective of the nature of the conduit. The fourth situation "subaerial deposition at ice front" is probably difficult to recognize as an esker.

These three basic models: *open channel* (fluvial), *tunnel* and *deltaic* provide the fundamental framework of reference for discussion of esker sedimentation. Each of these models is characterized by typical facies arrays, sedimentary structure assemblages, and paleocurrent patterns. The basic aim of this paper is to

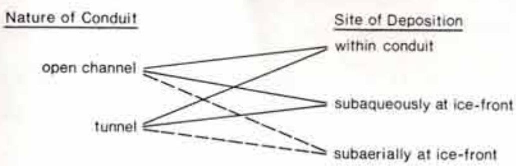


FIG. 4.—Models of esker sedimentation, based on nature of conduit and site of deposition. Dashed lines indicate poorly developed feature and improbable recognition of it as an esker.

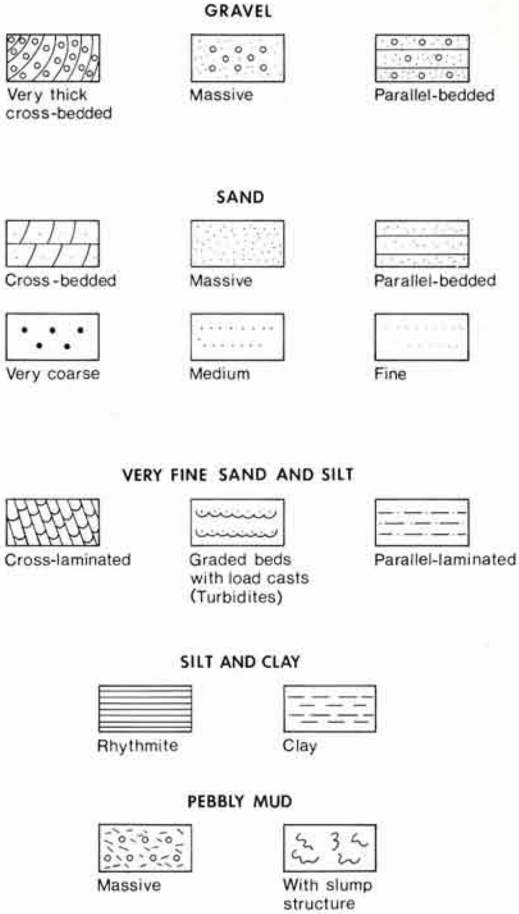


FIG. 5.—Facies types present in Peterborough and Windsor eskers.

analyze data provided by field studies of two eskers in Canada in terms of these proposed models.

FIELD EXAMPLES

Facies Types

Facies in the Peterborough and Windsor eskers have been differentiated on the basis of textures and sedimentary structures. Because most of the facies are common to both eskers, it is convenient to describe them before more specific discussion of facies relationships in the particular eskers. Facies types, and their symbols used in diagrams in the text, are summarized in Figure 5.

Gravel.—The most abundant facies are sandy pebble and cobble gravel and pebbly sand. Commonly the gravel has a very coarse sand matrix and a stable framework, that is, coarser clasts touch and support each other. In

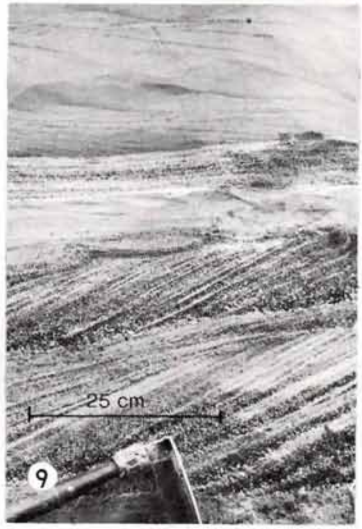


FIG. 6.—Very thickly cross-bedded gravel, Peterborough esker. Regressive ripples were observed at the toes of these foresets. (GSC 202287-B).

FIG. 7.—Gravel with vague bedding intensely deformed near proximal end of bead in Windsor esker, locality 5. Flow right to left. (GSC 202287-C).

FIG. 8.—Gravel showing faint parallel bedding and overall grading, Peterborough esker. Shovel is 50 cm long. (GSC 146968).

FIG. 9.—Sequence of cross-bedded and parallel-bedded medium to coarse sand and ripple-laminated fine to very fine sand, Windsor esker. (GSC 202287-D).

FIG. 10.—Sets of cross-bedded sand separated by thin units of ripple-laminated sand indicating forward migration of dunes with superimposed ripples, Windsor esker. (GSC 202287-E).

FIG. 11.—"Massive" or "structureless" sand unit deposited almost entirely directly from suspension, Windsor esker. (GSC 202287-F).

some localities, however, open-work pebble gravel has been observed to grade laterally over 2 m within one bed to pebble gravel with a silty sand matrix and then to a pebble gravel with a disrupted framework.

Cross-bedding is common in gravel facies. Set thicknesses range up to 7 m (fig. 6). Commonly pebble gravel beds that at first glance appear massive or "structureless," exhibit a vague but definite cross-bedding with set thicknesses of 50 to 60 cm. These probably record downstream progradation of bar fronts. Backset bedding, interpreted as being related to antidunes, was observed in sandy pebble gravel at two sites in the Peterborough esker (fig. 3). Massive gravel, and gravel with vague bedding chaotically deformed and slumped (fig. 7), is present at the proximal ends of beads. Gravel that is located stratigraphically near the base of the esker sequence is commonly parallel bedded and poorly sorted. Thick, parallel-bedded gravel units have been observed that are graded and become more distinctly stratified upward in sequence (fig. 8). The presence of a poorly sorted fine matrix suggests that these units may have been deposited rapidly from a slurry, perhaps generated by a subaqueous slump a short distance upslope.

Sand.—Sand occurs in a variety of grain size and sedimentary structure combinations (fig. 5). Cross-bedded sand is an abundant facies and is produced either by dune trains on the bed or by individual prograding sand-bar fronts. These commonly consist of downstream dipping foresets of medium to coarse sand with the coarsest material concentrated near the toe (fig. 9). Set thicknesses average 15 to 30 cm; usually the tops of the foresets have been truncated before deposition of the overlying set. The distinction between a dune and a bar front can be made at some localities by the use of related facies. Migration of dunes with superimposed ripples accompanied by appreciable aggradation of the bed produces sets of dune cross-bedded sand separated by thin units of ripple-laminated sand (fig. 10). Bar fronts, on the other hand, may show a much more complex array of associated bed forms. Aario (1972b, his fig. 1) has exhumed the actual bedding surface for several meters in the vicinity of such a bar front and has produced admirable evidence to explain facies arrays that the present authors have observed in both the Peterborough and Windsor eskers. In a downstream direction the succession of bed forms and structures was: (a) dunes and/or ripples build forward on the bed and deliver sand to the bar front leaving sets of cross-stratified sand on the bar top; (b) foresets of the bar front are straight or slightly concave upwards and occur, in the Windsor esker, in sets as thick as 2.2 m; (c) regressive ripples result from a backflow in the zone of flow separation and usually produce type B ripple lamination (Jopling and Walker, 1968) in the toesets; (d) the zone of zero velocity where the flow re-attaches to the bed produces a zone of polygonal nondirectional ripples. In section, these ripples have sharp crests and rounded troughs; as new sediment is deposited over these, sinusoidal ripples can be produced (the present authors have also verified this by exhumation of the bedding surface); and finally, (e) progressive ripples that migrate away from the bar front and produce type A or B ripple lamination.

"Massive" or "structureless" well sorted coarse, medium, or fine sand units (fig. 11) are also common in beads of the Windsor esker. Although not strictly "structureless," the absence of well defined lamination indicates the absence of a significant traction carpet. In most localities the units show a very vague parallel bedding. In some localities ripple lamination showing no stoss-side preservation passed upward into climbing ripples then faded out upwards into such a "structureless" sand unit. The angles of climb increased upwards to as much as 47 degrees before the distinct ripple lamination disappeared. This sequence is interpreted as recording an increase in the proportion of sediment falling directly from suspension onto the bed relative to the amount contributed by the traction load.

Parallel-bedded and -laminated coarse and medium sand (fig. 9) occurs associated with dunes and ripples. In most cases it appears from the associated facies to record a flat-bed condition in the lower part of the lower flow regime where the sediment was too coarse to permit development of ripples on the bed (Williams, 1967).

Very fine sand and silt.—Fine and very fine sand admixed with silt is commonly ripple-laminated and is widespread in both the Peterborough and Windsor eskers (fig. 12). The degree of stoss-side preservation changes with the proportion of sediment falling from suspension. Commonly the transition is from type A upwards to type B (fig. 13) and results from the approach of a larger bedform. Regressive ripples (fig. 14) occur in the zone of flow separation downstream from the crests of larger bedforms and record a backflow in this zone. They are common downstream from bar fronts.

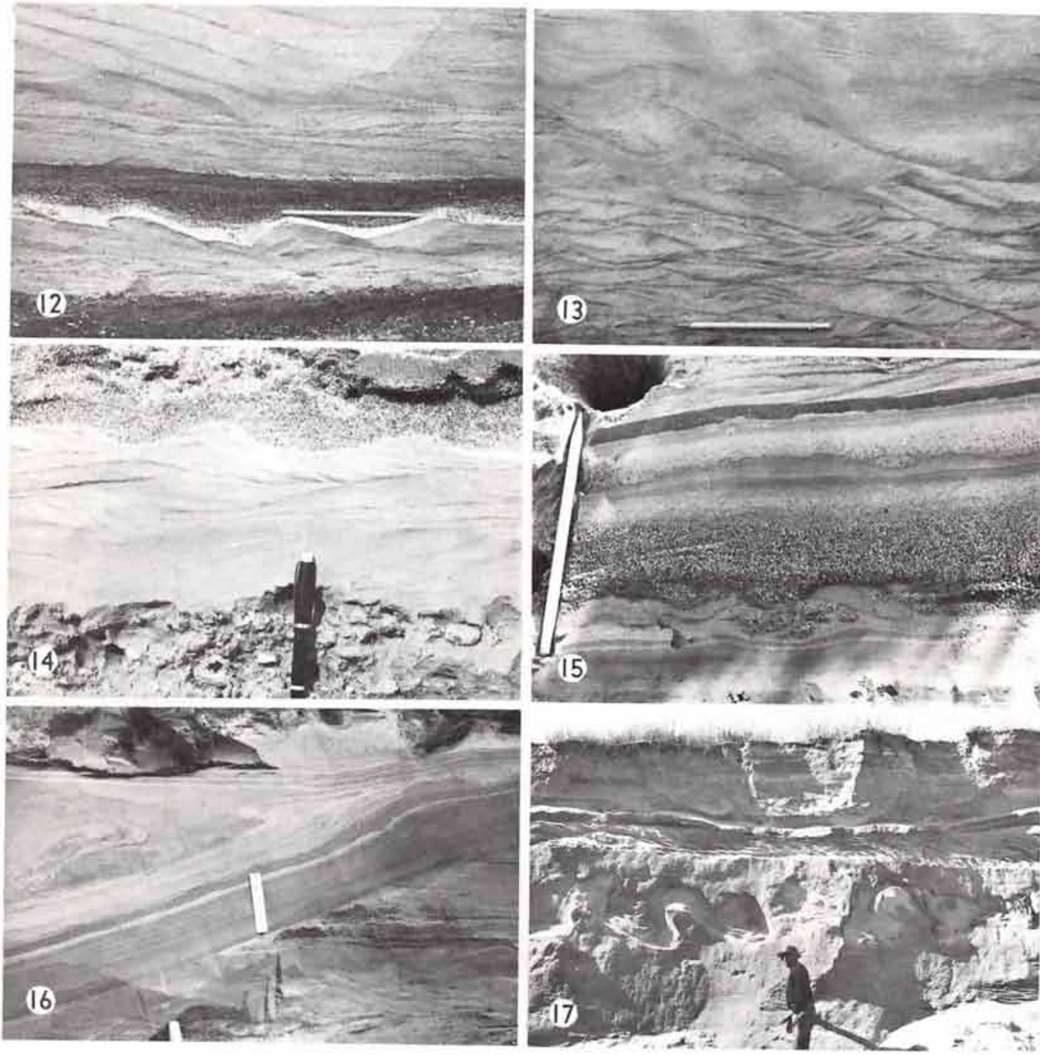


FIG. 12.—Ripple-laminated fine sand, Windsor esker. A climbing-ripple sequence (ripples have been exhumed) has been interrupted by the delivery of coarse sand that is parallel-laminated. (GSC 202287-G).

FIG. 13.—Ripple-laminated very fine sand showing gradual increase in stoss-side preservation upward in the sequence, Peterborough esker. (GSC 202287-H).

FIG. 14.—Regressive ripples formed in the zone of backflow at the toe of a large tongue of disrupted-framework gravel in a bead of the Windsor esker, locality 6. General flow direction in the bead was right to left. (GSC 202287-I).

FIG. 15.—Graded sand bed with load structures at base, bounded by parallel-laminated very fine sand and silt, Windsor esker. (GSC 202287-J).

FIG. 16.—Slump structure in sandy silt, Peterborough esker. Convolute laminations are present in sand immediately upstream (to right). Ruler is 15 cm long. (GSC 202287-K).

FIG. 17.—Slump structure in fine sand, locality 10, Peterborough esker. This unit was traced 50 m downstream (leftward) into a diamictic varve. (GSC 202287-L).

Many "hydroplastic" deformational structures are associated with very fine sand and silt units. Graded sand beds that overlie these fine-grained units commonly exhibit load structures at their bases (fig. 15). Where upward injection of the fluidized fines has kept pace with aggradation of the bed the tips of the diapirs are turned over in the direction of flow and the resulting flame structures are reliable paleocurrent indicators. Increase in bed velocity can create an oversteepened condition in fine material and produce downslope failure involving several laminations (figs. 16, 17).

Silt and Clay.—Rhythmically laminated sandy silt and clay (fig. 18) represent the most distal facies related to those eskers that are deposited in association with glacial lakes. In both the Peterborough and Windsor eskers, coarse-grained esker facies have been traced directly into rhythmite sequences.

Pebbly mud.—Pebbles floating in a muddy matrix (fig. 19) form a distinctive, though not common, facies. All examples of this facies type observed in the Peterborough and Windsor eskers contain moderately well rounded pebbles that are not striated. Also they occur in tabular strata-bound units. This suggests that they are the product of a mudflow process that incorporated stream-worked pebbles, and that they are not till units.

Peterborough Esker

The Peterborough esker (fig. 20) lies north of Lake Ontario and just north of the town of Peterborough. It is approximately 25 km long, including numerous gaps, and locally is as much as 1 km wide.. The esker is parallel to numerous well developed drumlins. Superimposed on the main broad ridge is a discontinuous prominent ridge and, in places, lower sharp sinuous ridges. The crest of the esker rises in a downstream direction from about 230 m a.s.l. to 275 m. Maximum relief of the ridge is 20 m. Numerous kettles and the occurrence of faults in the ridge sediments attest to its ice-contact origin.

Bedrock topography and thickness of the unconsolidated overlying sediments have been studied by Gagné and Hobson (1970). Ordovician limestone lies within 25 m of the ground surface in the vicinity of the esker and is exposed within 1 km of the esker on either side. The position of the esker appears to be unrelated to the subjacent bedrock topography, rather it trends indiscriminately across bedrock valleys and ridges (fig. 20).

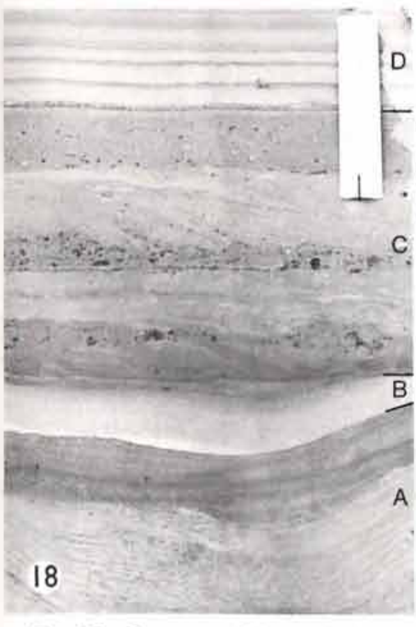


FIG. 18.—Sequence of fine-grained sediments, Windsor esker. (A) Very fine sand and silt with sinusoidal ripple lamination. (B) Graded bed of fine sand, probably a turbidite. (C) Three mud layers with floating clasts. (D) Graded, rhythmically laminated clay/silt couplets. Ruler is 15 cm long. (GSC 202287-M).

FIG. 19.—Pebbly mud in Peterborough esker. Shovel is 50 cm long. (GSC 202287-N).

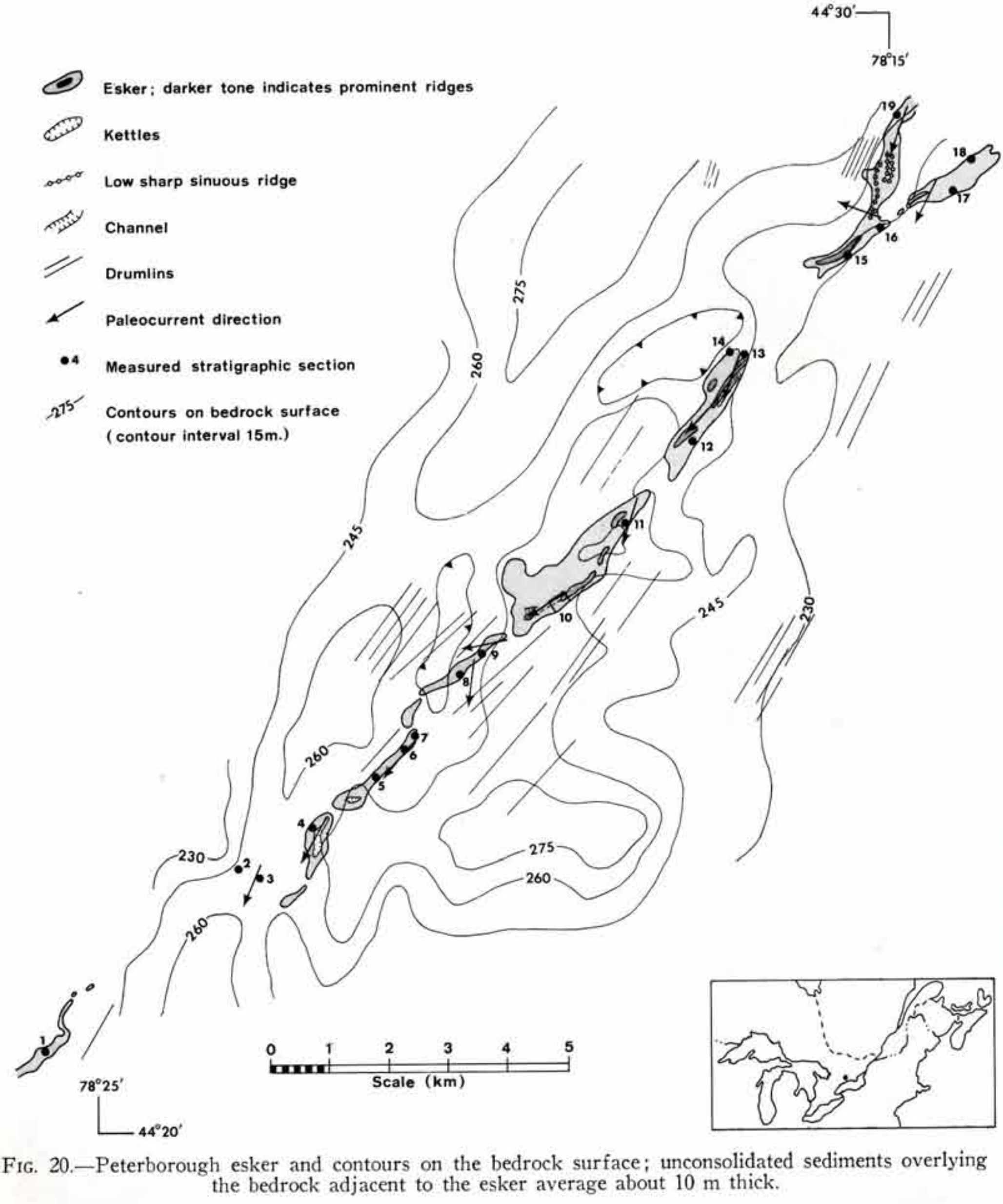


FIG. 20.—Peterborough esker and contours on the bedrock surface; unconsolidated sediments overlying the bedrock adjacent to the esker average about 10 m thick.

A large number of gravel pits provide well exposed sections through esker sediment. From these measured cross-sections a detailed picture of the stratigraphy has emerged. In the larger pits exposures continuous for 1 km permitted the tracing of individual beds. Sedimentary structures and facies relationships are summarized in Table 2.

Cross stratification is common at all scales up to 7 m (figs. 3, 6, 13). In most cases it represents the building forward of a deltaic front, bar front, or dunes. At localities 13 and 14, however, cross-beds of relatively poorly sorted gravel (fig. 3) are inclined in a direction opposite to the prevailing paleocurrent and have been interpreted as backset beds related to antidunes on the bed. This, in turn, provides evidence for open-channel flow since free-surface waves are necessary for their formation.

The most common facies array in the Peter-

TABLE 2.—SEDIMENTARY STRUCTURES IN THE PETERBOROUGH ESKER

Structure	Morphology	Grain size	Facies relationships
1. Parallel bed	Thickness: 20 to 40 cm Form: Planar Tabular	Gravel to coarse sand	Interbedded with 2 or 3
2. Very thick cross-bedding	Average thickness: 234 cm Form: Planar tabular	Gravel to coarse sand	Grades downstream to 4 to 5 Overlain by 3
3. Thick cross-bedding	Average thickness: 28 cm Form: Simple or planar tabular	Coarse to medium sand	Grades downstream to 5 Overlain by 3
4. Cross lamination	Average thickness: 3.5 cm Form: Ripple drift	Fine to very fine sand	Grades upstream to 2
5. Graded beds	Average thickness: 11 cm Form: Wedge-shaped, thins downstream, load structure at bottom	Very fine sand to silt	Grades upstream to 2 or 3 Grades downstream to 6
6. Rhythmic laminae	Average thickness: 3.0 cm Form: Tabular	Silt and clay	Grades upstream to 5

borough esker involves deltaic, or gravel-bar, fronts and the facies associated with them. Figure 21 depicts a sequence of four vertically stacked successions produced by this environment as the bed aggraded. Very thick cross-beds mark the bar fronts and cross-bedded sands on top record dune trains in the shallower water there. Downstream the facies change first to regressively then progressively ripple-laminated fine sand, then graded beds with load casts possibly indicating that subaqueous slumps on the bar front generated turbidity flows, and finally to rhythmically laminated silt and clay of a lacustrine environment.

The downstream relationship of relatively coarse-grained esker sediments with rhythmically laminated very fine sand, silt and clay illustrates the important genetic relationship between glaciofluvial and glaciolacustrine sediments. The development of a turbidity current

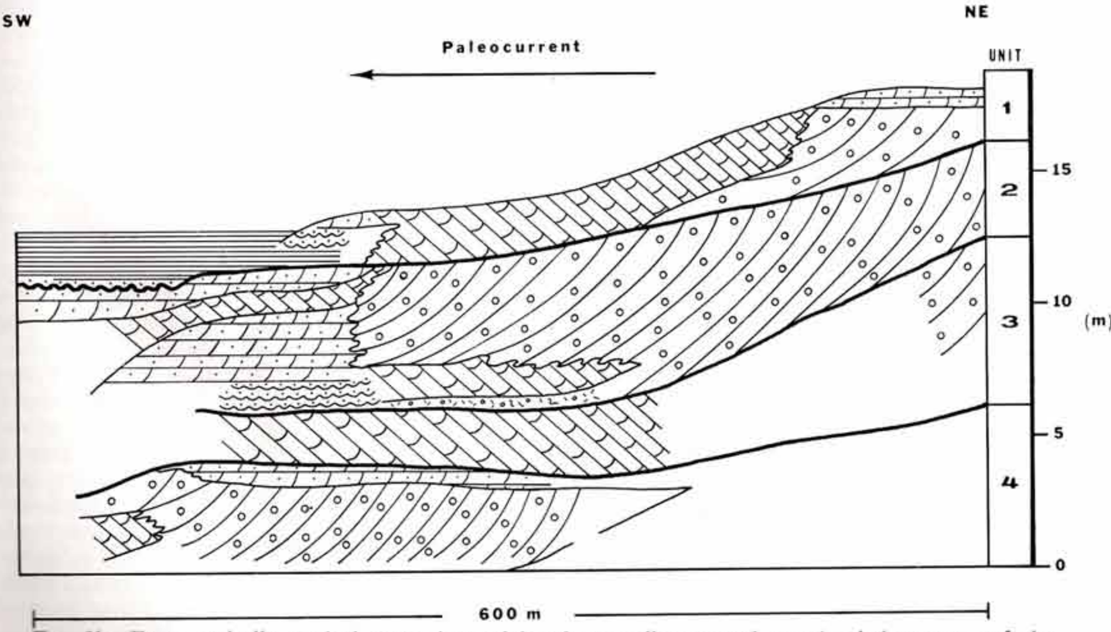


FIG. 21.—Four vertically stacked successions of bar-front sediments and associated downstream facies in the Peterborough esker, locality 10. Downcurrent facies change to finer sediments in conspicuous. For explanation of symbols see Figure 5.

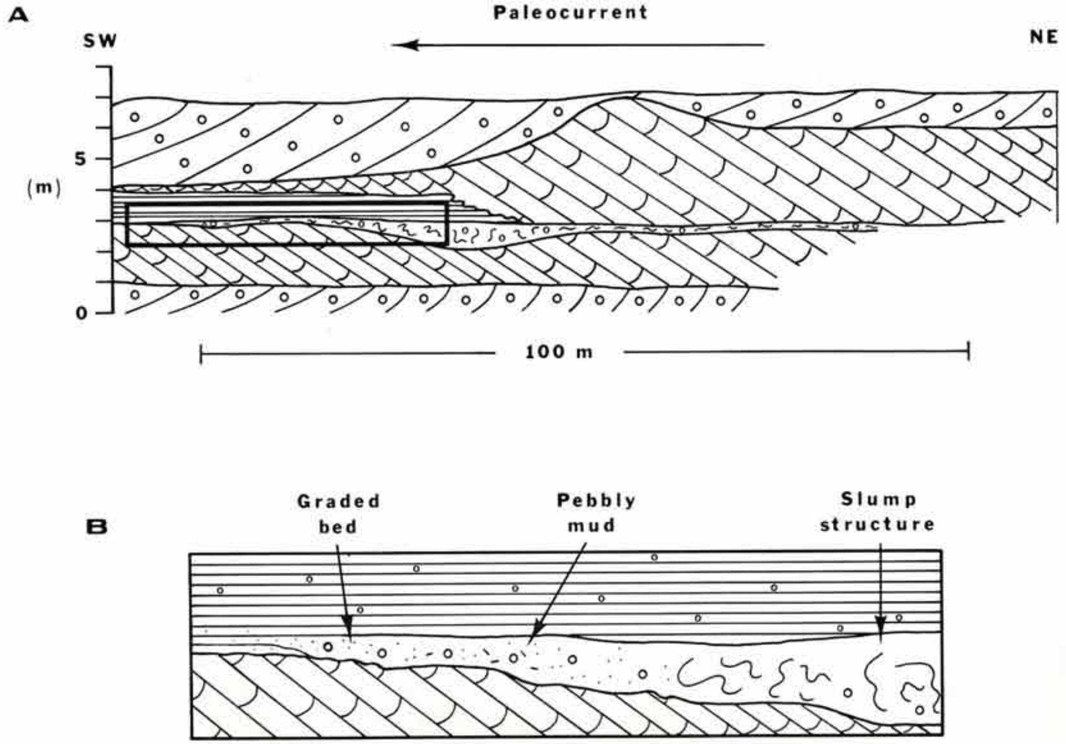


FIG. 22.—Change of facies in a single layer showing the transformation of a slump into a mudflow deposit and then to a graded rhythmite where final transport was by turbidity current; locality 10, Peterborough esker. For explanation of symbols see Figure 5. A, Stratigraphic framework. B, Enlargement of facies from area outlined in A.

from a subaqueous slump at the delta front is vividly depicted by a single layer which changed character within a short distance (figs. 17, 22A and B). At locality 10, across 50 m in a downcurrent direction, a slumped silty sand layer (slump) passed in a downcurrent direction into a pebbly mud with clasts of silt and very fine sand (mudflow) and then into a graded very fine sand layer with silt clasts (turbidity current) which, in turn, formed part of a diamictic rhythmite sequence.

A general trend to finer grained sediments higher in the section was pronounced and is attributed to retreat of the glacier which resulted in progressively more distal and finer grained sediments at a particular site.

Paleocurrents in Peterborough esker.—Paleocurrent directions shown on Figure 20 are vector means for each locality. They represent a total of more than 500 measurements of cross-strata dips. The overall vector mean is S 42°W, i.e. parallel with the esker trend; overall variance (based on the vector mean) is 4,723 and overall vector strength is 0.51. Variability of current direction within individual segments is commonly still higher. For example, the deltaic units depicted in Figure 21 have a variance and vector strength respectively of 5,509 and 0.49 for cross beds and 6,470 and 0.46 for ripple laminations (fig. 23). This variability is rather high for a unidirectional flow in a relatively short segment of a straight conduit but can be explained as being due to fanning out of flow at the delta head.

Environments of deposition in the Peterborough esker.—From the above observations it is apparent that the Peterborough esker was deposited in an open channel which formed a delta at the ice front where it discharged into a lake. The facies arrangement in the esker is a strong evidence in support of the partly deltaic origin. Higher variance in the paleocurrent data may also be a result of deltaic mode of deposition caused by fanning out of flow at the channel mouth. Subaqueous slumps, mudflows, and turbidity currents are more

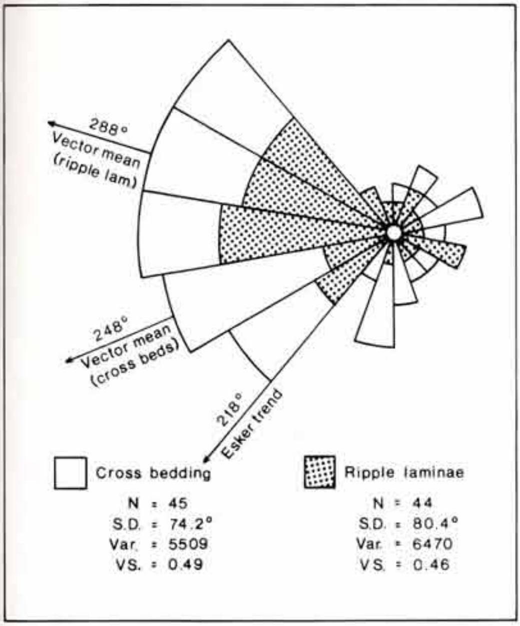


FIG. 23.—Paleocurrents from deltaic environment, locality 10, Peterborough esker. (N = number of observations; S.D. = standard deviation; Var. = variance; V.S. = vector strength.)

likely to occur at the delta front. Therefore, the above features of the Peterborough esker might be said to characterize a deltaic model of esker sedimentation.

Windsor Esker

The Windsor esker, 14 km in length, is situated near the bottom of the St. Francis River valley at the town of Windsor, Quebec (fig. 24). The esker was formed during final deglaciation of the Quebec Appalachians as the late Wisconsin ice front back-wasted northwestward down the gradient of the St. Francis River (McDonald, 1968). A glacial lake was impounded against the ice front during this retreat. In the vicinity of Windsor the depth of water at the ice front was 105 m.

The Windsor esker displays three different morphologic types: (a) Between localities 1 and 10 there are 16 beads, and localities 1 to 15 are mostly situated in beads. These beads are isolated from each other, each is 10 to 20 m high, and they have a regular spacing of 285 m; (b) From localities 16 to 22 and from 27 to 28 the esker consists of a fairly continuous single, steep-sided ridge, 10 to 20 m high, with sharp crest and uniform crest altitude; and (c) localities 23 to 26 are situated in a complex double ridge. No stream-deposited outwash terraces are present in the valley, rather, the esker is flanked by till and by very fine sand and silt deposited in the glacial lake.

Numerous bedrock exposures lie in the valley bottom and in the valley sides so it is clear that the Windsor esker lies in a bedrock valley. At locality 16, esker sediments lie directly upon slate; elsewhere bedrock is judged to lie within about 10 m below the base of examined esker sections.

Stratigraphy and facies relationships in the esker have been examined at 28 gravel-pit localities. All facies, summarized in Figure 5, are present in the esker. Graded beds and clay/silt rhythmites are much less common than in the Peterborough esker, but pebbly mud occurs much more frequently. "Structureless" sand units, not observed in the Peterborough esker, are common in beads of the Windsor esker. Because morphology of the esker is controlled largely by the shape of the primary depositional units, facies relationships will be discussed in terms of the three morphologic types.

Sediments within beads.—The sediments in beads show a very rapid downstream facies change. Massive, cross-bedded, or parallel-bedded proximal gravel passes downstream by way of interfingering into a section of fine- to medium-grained sand that is either "structureless," or that shows climbing progressive ripples. At the most distal portion of the bead very fine sand and silt rhythmites intertongue with and overlie these units. Thus the whole spectrum of the deposit illustrates rapid facies change at the mouth of the conduit with glaciofluvial sediments at one end and glaciolacustrine at the other, typifying a *deltaic model* of sedimentation.

Both longitudinal and transverse sections through a typical bead were exposed at locality 6 (fig. 25). Eighteen meters of vertical section at the upstream end of the bead are composed largely of "massive" to parallel-bedded and cross-bedded pebble and cobble gravel. Proximal gravel facies are characteristically intensely deformed and faulted (fig. 7). Proximal gravel units are characterized by upstream dips of *ab* planes of pebbles. Within 25 m in a downcurrent direction this coarse-grained section passes, by way of large-scale intertonguing subunits, into a section of climbing ripples and "structureless" units of fine and medium sand. Scour-and-fill structures, regressive ripples (fig. 14), slump structures, pebbly

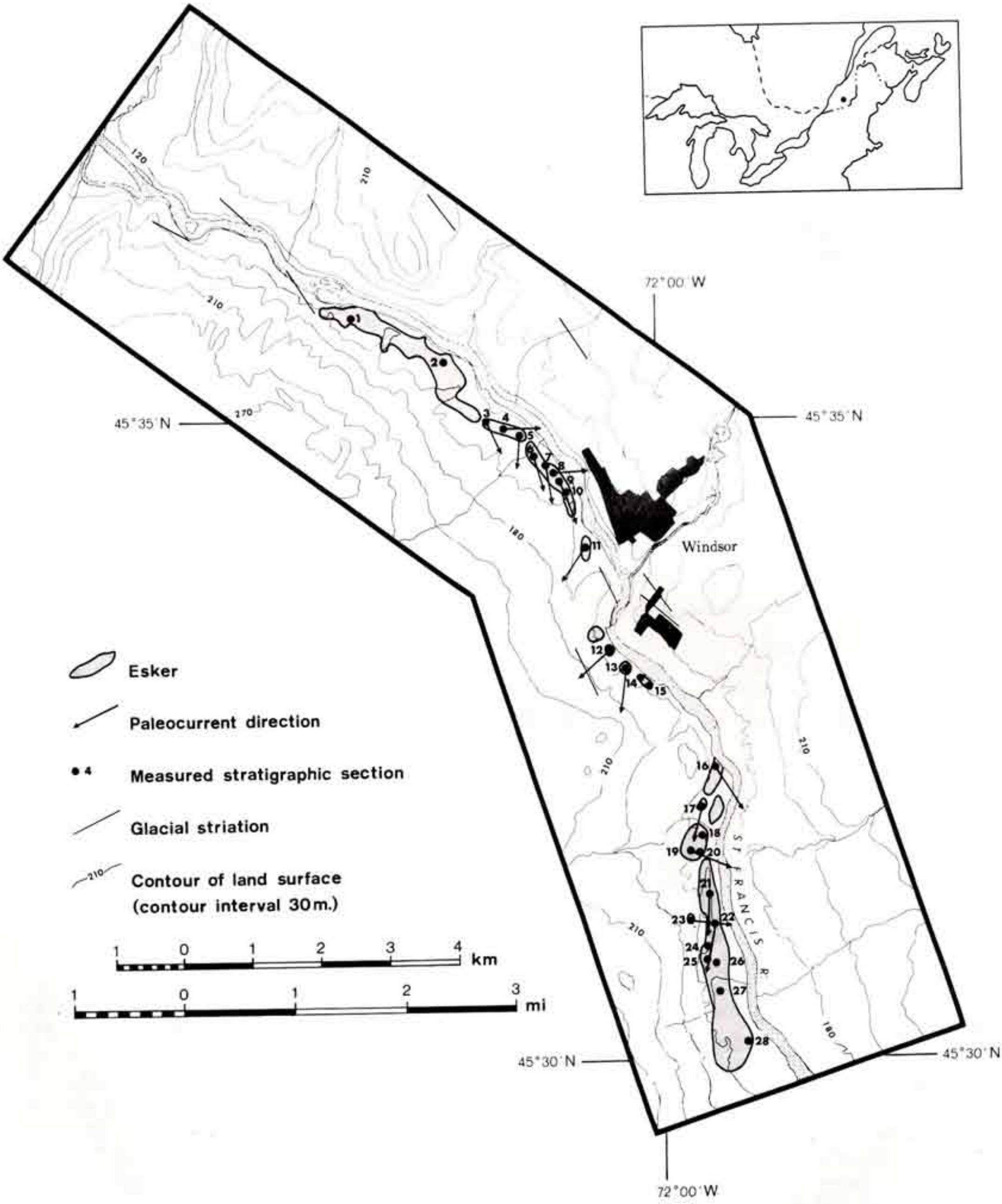


FIG. 24.—Windsor esker.

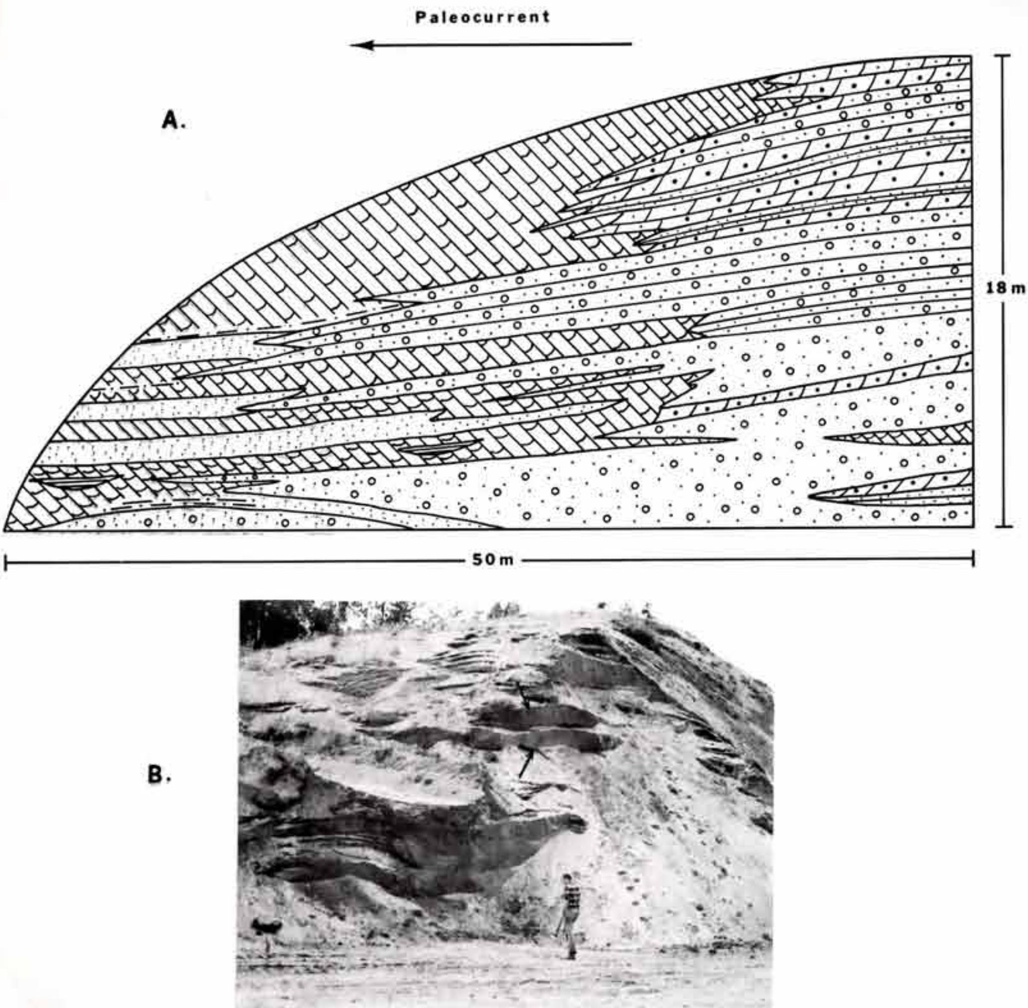
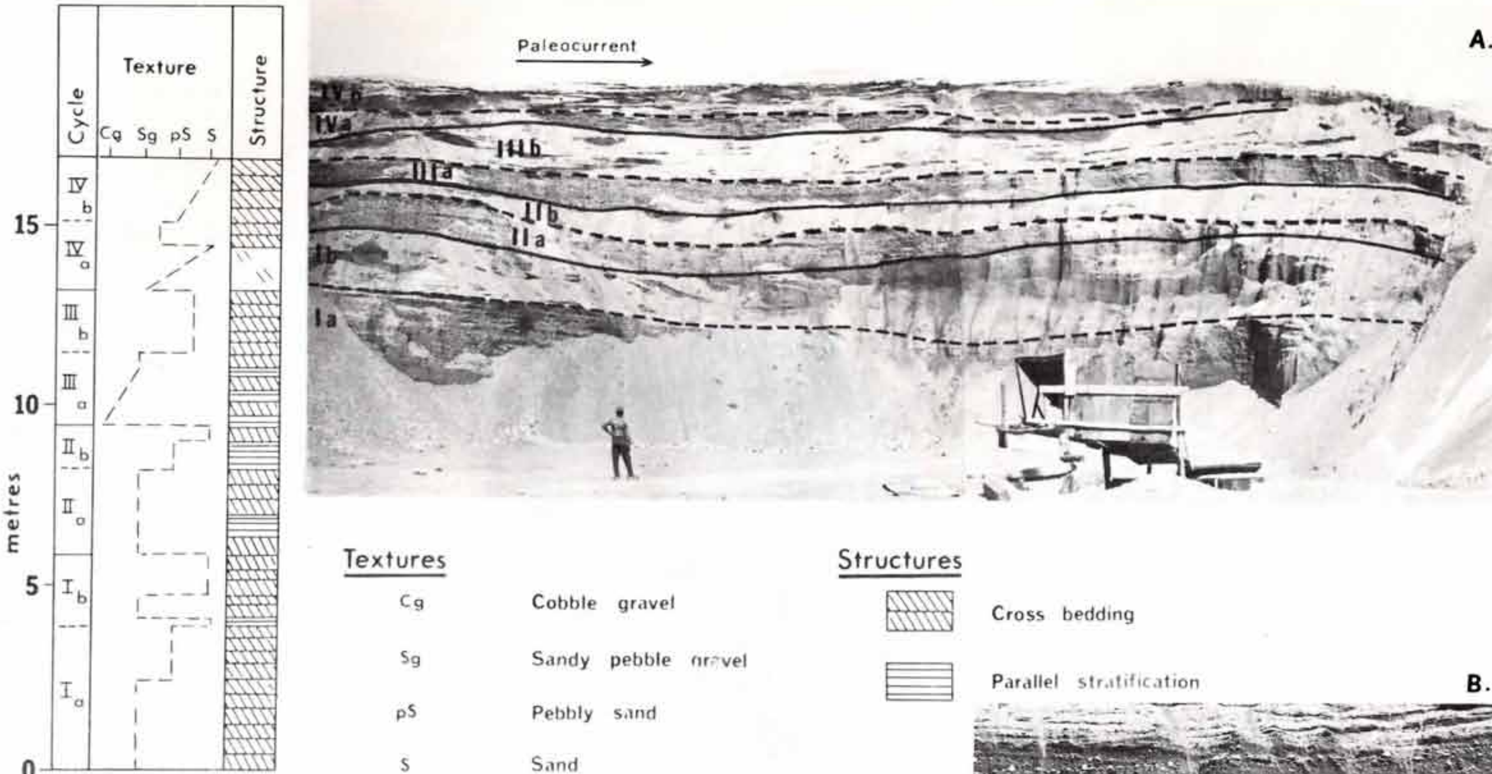


FIG. 25.—A, Longitudinal section through a typical bead in Windsor esker, locality 6. For explanation of symbols see Figure 5. B, Transverse section through bead at locality 6, Windsor esker. Prominent beds (see arrows) are "structureless" sand units. (GSC 202287-O).

muds, graded units, and rare frigites[3] occur near the downstream ends of large gravel tongues. Numerous "structureless" sand units, as thick as 75 cm, occur near the distal end (fig. 25B). Load casts at their bases attest to their rapid deposition, probably by turbidity current. Very fine sand and silt rhythmites intertongue with and overlie the most distal portion of the bead. A transverse section through the centre of the bead at locality 9 is shown by McDonald and Shilts (this vol., their fig. 5). Collapse features are not common on the sides of beads. Rather major normal faults are commonly situated near the crest and strike parallel to the esker trend.

Sediments within single steep-sided ridges.— In contrast to beads, single steep-sided ridges consist essentially of alternate tabular units of cross-bedded and parallel-bedded gravel and sand. Individual units persist for several tens of meters in longitudinal section with little change in thickness. In transverse section the subhori-

[3] *Frigites* is a term used by Barbour (1913) to mean a well defined mass (of boulder- or smaller size) of unconsolidated sediment, usually well stratified, the attitude of stratification and/or component grain size of which differs noticeably from the enclosing unconsolidated sediments; called a frigite where interpreted as having been emplaced as a clast while frozen.



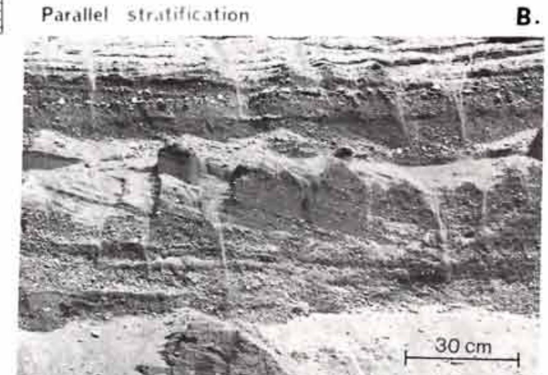


FIG. 26.—A, Longitudinal section through core of Windsor esker, locality 21, where esker is composed of a single sharp ridge and is judged to have been deposited in a subglacial tunnel. Note four vertically stacked sedimentation cycles. B, Parallel-bedded and cross-bedded pebbly sand from unit IIa, locality 21. (GSC 202287-P).

zontal units show only minor interfingering and are commonly truncated by high-angle reverse faults on the flank of the esker (McDonald and Shilts, this vol., their fig. 4 is from locality 21, Windsor esker). Scour-and-fill structures are not prominent. At most localities there is a tendency for the section to become finer grained upwards.

At locality 21 is a particularly good longitudinal exposure 60 m long (fig. 26A) through the core of a single steep-sided ridge that has a total continuous length of 640 m. The ridge consists of cyclical sedimentation units (four cycles exposed) that are persistent with little change in texture, structure, or thickness for at least 60 m in a downcurrent direction. Each cycle is characterized by cobble or pebble gravel at the base passing upward into sand or pebbly sand. Thickness of the cycles varies from 3.6 to 5.9 m. Average downcurrent dip of general bedding contacts is 8 degrees ($N = 12$). Cross-beds (fig. 26B) occur in tabular sets; straight foresets become tangential at the base and commonly are truncated at the top, although stoss-side preservation has been observed. Set thicknesses in sand subunits range from 17 to 53 cm and average 28 cm ($N = 14$); set thicknesses in gravel subunits range from 5 to 120 cm and average 40 cm ($N = 25$). The intermediate axes of ten rounded cobbles near the bases of units Ia, IIa, IIIa, and IVa averaged 11.2, 10.6, 14.3, and 7.6 cm, respectively. Pebbles in gravel foresets have long axes parallel to the flow direction and have their *ab* planes in the plane of the foreset. A thin (<50 cm) veneer of lacustrine sand mantles the ridge.

Sediments within complex double ridge.—Double-ridge portions of the esker appear to be considerably more complex than do either single ridges or beads, and exposures were not extensive enough to unravel the complexity. Neither cycles nor broad textural changes were discernible. Lateral and vertical facies changes occur abruptly through both interfingering and gradation. Intensely deformed clay/silt rhythmites have locally been introduced from beneath up into the esker sequence. Paleocurrent measurements (locality 23, fig. 24) locally indicate flow at a high angle to the esker trend, suggesting that flow may have occurred between two adjacent meltwater arteries.

At locality 26, more than 10 m of undeformed parallel-bedded and cross-bedded cobble gravel is abruptly overlain by 5.3 m of silty very fine to medium sand that has been so intensely folded and faulted that only rarely can primary sedimentary structures be recognized,

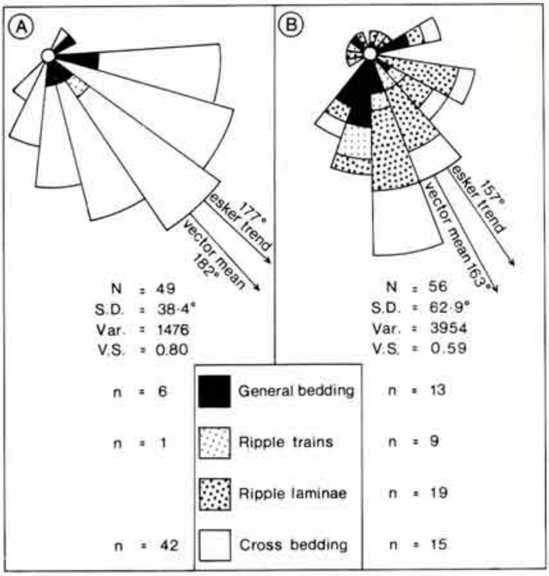


FIG. 27.—A, Paleocurrents from single ridge (tunnel) environment, locality 21, Windsor esker. B, Paleocurrents from bead (deltaic) environment, locality 6, Windsor esker. (N, n = number of observations; S.D. = standard deviation; Var. = variance; V.S. = vector strength.)

although gross subunits can be traced laterally for several meters. This is the only site observed in the Windsor esker where collapse of an ice roof with consequent lowering of superimposed lacustrine sediments seems to have affected the esker sediments.

Paleocurrents in Windsor esker.—Paleocurrents were determined from measurements of azimuths of cross-beds and ripple laminations and lee directions of ripple trains. Because of their contrasting characters, beads and ridges were treated separately. Approximately 50 measurements were taken from each bead and each ridge. An attempt was made to collect data equally from all units exposed in the sequence. The data from a typical ridge and a typical bead are shown in Figure 27. In all cases vector means of paleocurrents lie close to the trend of the esker (fig. 24). Significantly, the beads and ridges differ markedly in their measures of paleocurrent variability. The variability values do not overlap. This difference between beads and ridges could facilitate environmental discrimination between a tunnel and a deltaic model as described later.

Paleocurrents from single ridges have variances (based on vector mean) of between 1,000 and 2,000 and vector strengths of about 0.80. The variability measures shown in Figure 27A were calculated separately for the cross-bed data there; the values were identical with those for the entire sample.

Paleocurrents from beads have variances generally between 3,000 and 4,000 but may go above 6,000. Vector strengths are less than 0.65. The breakdown of variability measures for particular sedimentary structures at locality 6 (fig. 27B) were, for general bedding, ripple laminations, and cross-bedding, respectively: variance = 4,062, 1,257 and 5,845; vector strength = 0.59, 0.83, and 0.43. Ripple laminations were measured mostly in the upper 15 percent of the section which may account for their low variability.

Paleocurrent measurements from one bead, locality 9, were plotted according to their stratigraphic position in the bead. This revealed that flow initially was deflected to the right of the mouth of the conduit and, after a significant sediment pile had accumulated there, flow was deflected toward the left. In addition to providing details of local sedimentation history, this points out that changing current systems must be recognized in an adequate sampling design.

Environments of deposition in the Windsor esker.—Sediments of the Windsor esker appear to have accumulated in two basically different environments of deposition: (a) at the points where flow in subglacial tunnels debouched into the glacial lake at the ice front; and (b) within subglacial tunnels.

Beads are clearly deposited in an environment characterized by rapid deceleration of flow. The proximal end of a bead is deposited in contact with ice and the distal end interfingers with lake-bottom sediments. Cross-bedded facies occur only at the proximal ends of the beads where they indicate the former presence of bars, and also possibly dunes, in a zone of rapidly varied flow with diverging flow lines. Preservation of even the most delicate sedimentary structures indicates that beads accumulated on the lake bottom and at the base of the glacier. A representation of this environment is shown in Figure 28. The relatively large variability of paleocurrent measurements results from expansion of flow as the lateral constraint of the tunnel walls is removed. Each bead represents a complete sedimentologic system, thus preventing correlation of sedimentation units from bead to bead.

These beads are subaqueous fans, or deltas, similar to the "ose centra" or "submarginal deltas" of De Geer (1940) who considered them to represent annual depositional events at the ice front. An annual periodicity for the beads near Windsor is also probable. The ice front retreated from the International border to the St. Lawrence Lowland, a distance of 100 km, in 400 C^{14}-years (Gadd and others, 1973). This gives an average retreat rate of 250 meters per year. The average spacing of thirteen successive beads in the Windsor esker is 285 m.

A subglacial-tunnel model alone fits the evidence from the single steep-sided ridges and, to some extent, from the complex double ridge. The glacial lake stood 105 m deep against the ice front, yet only at locality 26 is there evidence, albeit restricted to the upper 5.3 m of section, for pervasive deformation in the sediments. Elsewhere, even the most delicate primary sedimentary structures are preserved. This, and the presence of varve diapirs in sediments of the double ridge indicates that the esker stream flowed at the base of the glacier. The downstream persistence of high stream competence is evident from sediments at locality 21 (fig. 26A). In addition, low variability of paleocurrent indicators would reflect a unidirectional flow laterally constrained by ice walls of the tunnel. Faults in the flanks of these ridges record subsequent melting of these ice walls.

Several interesting questions arise, such as the depth of flow in the tunnel, the significance of the sedimentary cycles exposed at locality 21 (fig. 26A), the distance back from the ice front that escape of meltwater was localized in basal tunnels, and the manner in which these basal tunnels extended themselves headward as the ice front wasted back.

Evidence from pipe-flow experiments has been cited from McDonald and Vincent (1972) to show that actual water depth in the tunnel would be 2 to 10 times dune height. At locality 21, bed-form heights of 40 cm throughout a vertical section 16 m high indicate flow depths of 1 to 4 m. Water depth in the lake at the terminus was 105 m. This is strong corroborative evidence for flow having occurred in a tunnel. The absence of scour-and-fill structures indicates a relatively constant aggradation. Alternation of cross-bedding and parallel-bedding indicate (McDonald and Vincent, 1972) that hydraulic mean depth was maximized during this aggradation. It is suggested that accumulation of sediment occurred by low transverse bars migrating down in the tunnel, and that this deposition was accommodated by a melting upward of the ice roof. Thus a sedimentary sequence 15 to 20 m thick could accumulate even though flow depth at any one time was less than 4 m.

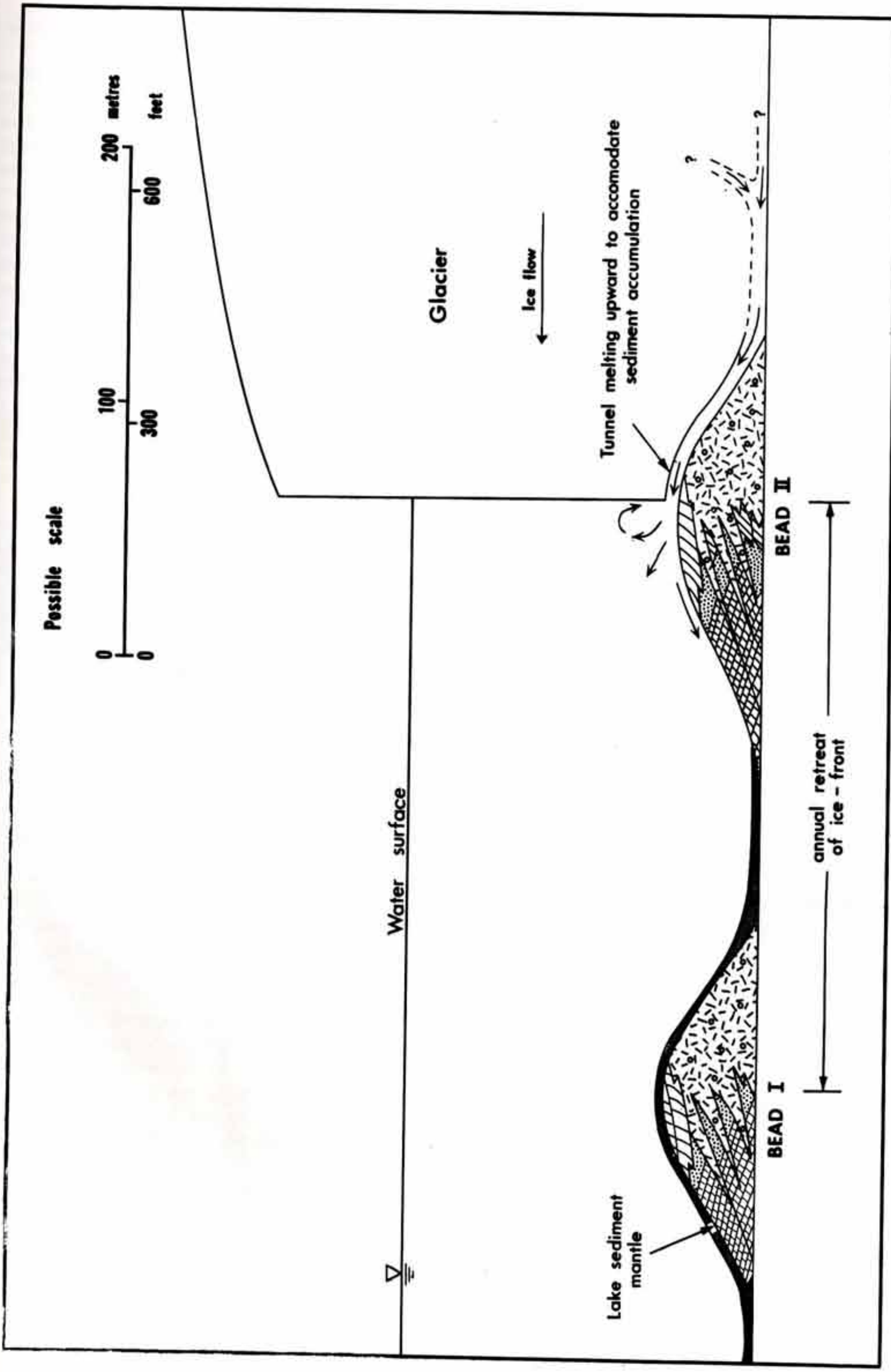


FIG. 28.—Generalized model of esker-bead formation.

Each of the four distinct cycles at locality 21 (fig. 26A), records an initial high stream competence that persisted downstream but that gradually decreased through time, leaving a unit that became finer grained upward. It is tempting to relate this to a cyclical fluctuation of discharge that, in glaciers, could either be diurnal or annual. Thickness of the units, and the observation that at least four cycles underlie a ridge 640 m long where annual retreat of the ice front was about 250 m, favor an annual periodicity.

The question of how far back from the terminus of an active glacier did a tunnel extend at any one time is difficult to answer from sedimentary structure data without an unusually long and good exposure. The ridge of which locality 21 is part is 640 m long and quite uniform in external morphology. This might provide a minimum figure. A study of the occurrence of certain rock types in the bedrock compared with the occurrence of pebble lithologies in the Windsor esker indicates that this distance may be more in the order of 3 to 4 km (Shilts and McDonald, 1975). The length and time-transgressive character of most eskers indicates that subglacial tunnels extend themselves headward as the ice front recedes. The details of this extension are unknown.

DISCUSSION

Sedimentary features of the two eskers studied have permitted interpretation of the basic factors of esker sedimentation: the nature of the conduit and the site of deposition. Facies arrangements in the two eskers were interpreted in terms of three basic models of esker sedimentation: open channel (fluvial), tunnel, and deltaic. An attempt will be made here to summarize the characteristics of each model:

(a) *Open-channel model*—Esker streams that flow in open channels would almost certainly be braided due to steep slopes and high bedload discharge. It is believed that the Peterborough esker formed partly in an open channel. The principal evidence for this is the presence of backset beds which have been related to antidunes and to waves on a free water surface. Lateral facies relationships that indicate lateral fining (Shaw, 1972) or overbank flooding from a central channel (Saunderson and Jopling, 1970) may also be present in an open-channel deposit although, as Allen (1965, p. 163) has pointed out, overbank deposits are only rarely preserved in a braided environment. Depositional units would be lenticular in transverse cross-section and more tabular in longitudinal section.

(b) *Tunnel model*—Single steep-sided ridges in the Windsor esker are believed to be deposited in subglacial tunnels. The characteristics of this model are: (i) tabular and longitudinally persistent units of parallel- or cross-bedded sand and gravel; (ii) absence of finer sediments such as very fine sand, silt, and clay; and (iii) low variability of paleocurrent directions (variance based on vector mean lies between 1,000 and 2,000; vector strength is about 0.80).

(c) *Deltaic model*—Many stratigraphic units in the Peterborough esker and the sediments in the beads of the Windsor esker are believed to be of delta origin. The characteristic features are: (i) rapid downstream facies change through gradation and interfingering from proximal gravel to lake-bottom rhythmites composed of silt and clay; (ii) occurrences of deposits caused by slump, mudflow, and turbidity current; (iii) large variability of paleocurrent directions (variance greater than 3,000; vector strength less than 0.65); and (iv) typical morphological expression as separate beads, as in the Windsor esker. However, when the deltaic units are juxtaposed they form a continuous ridge as in Peterborough.

Despite the widely held view that the associated glacier be stagnant in order for prominent eskers to form, there is nothing in the mechanics of formation that requires this. The view arose from consideration of the amount of meltwater required and the thought that flowing ice would destroy esker accumulations. Beaded eskers indicate, however, that the associated ice fronts were well defined and subject to regular backwasting. Accumulation in beads took place right at the ice front and was not subject to destruction by flowing ice. Even within the glacier, the ability of flowing water to maintain a conduit far exceeds that of the ice to close it by creep (Röthlisberger, 1972).

Similarly the presence of a standing water body at the terminus is not necessary, but it increases the chances for preservation of an esker by immediately placing the newly emerged esker in a low energy environment, removed from the erosive potential of proglacial braided streams.

Eskers are time-transgressive features with the downstream portion being the oldest. This is clear from the process of bead formation and also would offer an easy explanation for the formation of very long eskers such as the Thelon esker.

Additional detailed sedimentary studies of eskers are required, especially from a wide range of deglacial environments, in order to outline more fully the environments of formation and how these can be recognized. These will add to the usefulness of eskers in studies related to drift prospecting, groundwater, and regional geologic history.

CONCLUSIONS

1. Eskers are the products of a highly organized meltwater-flow system within the glacier and are common where an abundant supply of meltwater was available during deglaciation. They do not require that the glacier was stagnant, nor that there was a body of water ponded at the ice front.

2. External morphology of the esker complex is controlled to a large degree by the shape of the primary depositional units; both are closely related to the nature of the conduit, the site of deposition, and to whether or not a standing body of water abutted the ice front.

3. Different combinations in the nature of the conduit (open channel or tunnel) and the site of deposition (within conduit or at ice front (define three basic models of esker sedimentation: *open channel, tunnel,* and *deltaic*. Each model is characterized by typical sediments, facies arrays and paleocurrent patterns.

4. Eskers are time-transgressive, the downstream portion being the oldest; they appear to have formed either at the ice front or within 3 to 4 km of it during deglaciation.

5. The eskers examined in detail were deposited in contact with the glacier base; diapiric intrusion of underlying rhythmites upward into esker sediments locally supports this conclusion. Only rare components of the eskers showed intense deformation attributable to wholesale collapse as underlying ice melted.

6. The Peterborough esker was deposited, at least partly, in an open channel constrained laterally by ice walls. Backset beds are related to antidunes in the channel. Dunes and ripples delivered sediment to bar and delta fronts. The main foresets pass downstream into regressive ripples, sinusoidal ripples, progressive ripples, graded beds with load casts, and finally to rhythmically laminated silt and clay. This facies arrangement typifies the deltaic model.

7. A further type of deltaic model is represented by beads in the Windsor esker that were deposited annually where the subglacial tunnel delivered sediment to the lake abutting the ice front. Cobble and pebble gravel at the proximal end of the bead intertongues over a few meters in a downstream direction with ripple-laminated fine sand, units of "structureless" fine and medium sand, and graded beds, providing clear evidence of rapid deceleration of flow.

8. Examples of the tunnel model are provided by sediments in single, steep-sided ridges of the Windsor esker. Sheet-like cross-bedded and parallel-bedded sand and gravel units are persistent downstream. They occur in vertically stacked cycles that may have an annual periodicity. Flow depth in the tunnel was 1 to 4 m, and accumulation of sediment was accommodated by a melting upward of the ice roof.

9. Paleocurrent variability has proven useful in discriminating between depositional environments. Paleocurrent patterns in tunnels have a vector strength about 0.80 and a variance (based on vector mean) of 1,000 to 2,000. Paleocurrent patterns in esker deltas have vector strengths less than 0.65 and variances of greater than 3,000.

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