THE FORMATION OF ESKERS BASED ON THEIR MORPHOLOGY, STRATIGRAPHY, AND LITHOLOLOGIC COMPOSITION, LABRADOR, CANADA

by

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ABSTRACT

The distribution and drainage patterns of eskers in Labrador, as well as the morphology, stratigraphy and lithologic composition of five systems located in central («Gabbro» and «Ossokmanuan» eskers), western («Shabogamo» and «Ashuanipi» eskers) and northern Labrador («Lac Brisson» esker) were investigated to propose a model of esker formation and debris entrainment. Eskers are not uniformly distributed, and are more abundant on plateau areas while they are scarce to absent in mountainous terrain, near all coasts, and in a region centred over the presumed ice divide of the Labradorean sector of the Laurentide Ice Sheet. Eskers show a Horton drainage organization with up to third order segments (7 of 25 systems have 3rd order segments). Organized esker systems are up to 400 km long, and service a subglacial drainage basin of up to 17,000 km^2. Eskers are coarse-grained tunnel deposits, steep-sided, sharp-crested, straight (SI ~ 1.07) single ridges, which pass into less than 5 km long double or multiple segments. Associated with esker ridges are finer-grained proglacial and supraglacial fluvioglacial deposits such as aprons lapping on to the ridge; flat pads, separated from the ridge by a shallow ditch; splays, highly kettled deposits otherwise resembling pads; and blankets of gravel which may or not mask older deposits. Adjacent associated deposits were formed after the sedimentation of the ridge. Lithologies found in an esker ridge are derived from up-esker till (in a corridor up to 3.5 km on either side of the ridge) which is itself derived from bedrock. Esker are deposited by the laying of shingle-like tabular sedimentation units in a subglacial tunnel (25-30 km long) near the margins of the ice sheet.

RÉSUMÉ

La distribution et les patrons de drainage des eskers au Labrador, de même que la morphologie, stratigraphie et composition lithologique de cinq systèmes d'eskers au Labrador central (les eskers «Gabbro» et «Ossokmanuan») occidental (les eskers «Shabogamo» et «Ashuanipi») et nordique (l'esker «Lac Brisson») ont été étudiés afin d'élaborer un modèle de formation des eskers. On retrouve un plus grand nombre d'eskers sur les plateaux qu'en régions montagneuses, en bordure des côtes et dans la région de partage glaciaire du secteur du Labrador de l'Inlandsis Laurentidien. Les eskers montrent un système d'organisation de type Horton dont certains segments sont du troisième ordre (7 des 25 systèmes ont des segments de 3^e ordre). Les systèmes d'esker qui montrent cet organisation sont jusqu'à 400 km de long, et desservent un bassin de drainage sous-glaciaire allant jusqu'à 17,000 km^2. Les eskers sont des dépôts grossiers sédimentés dans des tunnels sous-glaciaires, sous forme d'une crête saillante à flancs abrupts, peu sinueuse (IS ~ 1.07). Des segments (< 5 km long) à crête double ou multiple sont également présents. Des dépôts fluvio-glaciaires proglaciaires et supraglaciaires à grains fins sont sédimentés postérieurement à la sédimentation de la crête et se retrouvent sous forme de tabliers qui recouvrent partiellement la crête, de bourrelets plats séparés de la crête par un fossé peu profond, d'évasements à kettles, et de couvertures qui peuvent ne pas masquer les dépôts antécédents. Les lithologies représentées dans la crête sont fonction du till en amont et dans un corridor de 3.5 km de chaque côté de la crête, qui, eux, dépendent de la roche en place. Les unités de sédimentation tabulaires sont disposées comme la pose de bardeaux dans un tunnel sous-glaciaire de 25-30 km de long, à partir de la marge glaciaire.

INTRODUCTION

Objectives

Eskers have long been recognized as a fluvioglacial landform characteristic of continentally glaciated terrain (Flint, 1943; Charlesworth, 1957; Price, 1973). They represent one of the most important deglacial landforms of the Laurentide and Fennoscandian ice sheets (Sugden and John, 1976, pp. 264-270). The origin of eskers is the subject of ongoing debate (Price, 1973; Stoelting, 1978; Ringrose, 1982; Shreve, 1985; Aylsworth and Shilts, 1989; Hebrand and Åmark, 1989). Despite their size, common occurrence, and economic importance, fundamental questions on flow of meltwater, origin and entrainment of glacial debris, and fluvioglacial environments of deposition, all of which bear directly on the formation of eskers, have not been answered. Modern eskers are occasionally associated with alpine glaciers and small ice caps, but they do not appear to be good analogues of the Pleistocene eskers, which formed in association with ice sheets of vastly greater areal extent. Modern eskers do not appear to be abundant, yet ancient ones are ubiquitous in glaciated areas. Some of the modern eskers appear to be supraglacial, yet most evidence bearing on the origin of ancient eskers point to a subglacial origin. The present, however, is the key to the past, and what little inference that can be made from modern to fossil eskers is to be viewed as a piece of the solution.

This research is an investigation of the origin of esker systems in Labrador, focusing on their distribution in the context of bedrock topography and ice sheet morphology, and their morphology, internal stratigraphy, and lithologic composition with respect to till and bedrock. The observations and analysis provide the basis for a model of esker formation. The questions addressed relate to the location of formation of eskers within the ice (supraglacially, englacially or subglacially), the depositional environments (open channel versus tunnel deposition), the length of tunnel in which eskers are forming, the conditions of the ice sheet during the formation of the eskers, and where and how debris is incorporated, transported, and deposited in the system. To know how eskers are formed is critical to our understanding of late glacial dynamics and ice sheet decay, and will contribute to the knowledge on ice sheets in general, and the Laurentide Ice Sheet in particular. Understanding how

debris is incorporated into esker systems may also be used, for example, by the mineral exploration industry to trace mineralized debris from its location in an esker system back to its origin in bedrock.

Eskers have almost always been defined by varied criteria, and are described as long, narrow, sinuous ridges (landform) of fluvioglacial (origin) sand and gravel (material) (eg.: Close, 1866; Crosby, 1902; Flint, 1930; 1971, p. 214; Hanson, 1943; Banerjee and McDonald, 1975; Embleton and King, 1975, p. 467; Ritter, 1978, p. 410; Drewry, 1986, p. 152; Henderson, 1988; Ashley *et al*, 1991). Their can be confusion as to what constitutes an esker due to the variety of morphologies and sedimentological characteristics within and between esker ridges and other types of fluvioglacial deposits (Stoelting, 1978). Charlesworth (1957, p. 416) suggested use of the term «esker» for all accumulations of fluvioglacial sand and gravel, and the use of the term «*os*», plural «*osar*», for the ridge itself. Although those terms have used in the Scandinavian literature, most North-Americans use the term «esker» for linear accumulations of fluvioglacial sand and gravel. Eskers are defined here as narrow (with respect to the length of the feature) ridges, primarily composed of coarse sand and gravel (Appendix I). The most common characteristics of eskers are their linear form, steep flanks, sharp crests, abundance of coarse debris (pebbles and larger), and orientation sub-parallel to late ice flow direction. Genetically, eskers are subglacial meltwater stream deposits and may be associated with other types of fluvioglacial sediment and landforms that, in combination, form an esker complex.

Location

Numerous esker systems are found in Labrador, especially in the interior, relatively flat, lake plateau physiographic region. There are a few settlements in Labrador, and most of them are located along the Labrador Coast, so that most of the interior land has not been substantially modified by human activities. Air photo coverage (1949-1979) exists for the area, and there are indicator lithologies, located close to esker systems, that can be used for compositional and entrainment studies. All eskers located in Labrador were used in the overall study of esker patterns, while seven esker systems («Gabbro» and «Ossokmanuan» eskers, in central Labrador; «Shabogamo», «De Mille»,

«Moose Head» and «Ashuanipi» eskers, in western Labrador, and «Lac Brisson» esker, in northern Labrador; Fig. 1) were the focus of more detailed work. These seven esker systems were chosen because of their accessibility, and underlying varied bedrock geology.

GENERAL GEOLOGY

Physiography

The physiography of Labrador has been described by Douglas and Drummond (1955) and Hare (1955; 1959), and summarized by Bostock (1967; 1969) and Greene (1974). The Labrador Peninsula is located on the Canadian Shield, which is characterized by an even, monotonous skyline broken by a few monadnocks and ranges of hills (Bostock, 1969). It has been subdivided in a number of physiographic areas, amongst which the George, Kaniapiskau and Lake plateaus are relevant to this study (Fig. 1).

Central and western Labrador are located on Lake Plateau (Bostock, 1969), which is a slightly subdued, drift-covered part of the main Labrador peneplain (Hare, 1959). The northwestern-most part of western Labrador is located on Kaniapiskau Plateau (Bostock, 1969) or Upland (massif-type upland of Greene, 1974), which is composed of rugged hills with an etched fracture system. A steep escarpment marks the boundary between the Kaniapiskau Plateau, which has an average elevation of 750 m asl, and Lake Plateau, which has an average elevation of 500 m asl. In both areas, average local relief is 150 m. Across central Labrador, average elevations decrease eastward, from 500 m asl to approximately 350 m asl. Near Churchill Falls, the deeply entrenched (360 m) Bowdoin Canyon, head of the Churchill River, and a few unnamed canyons of comparable depth, are located near the terminus of Gabbro esker system. Bowdoin canyon and others are controlled by bedrock structures and trend roughly east-west. The Lake Plateau has numerous lakes and rivers, as well as abundant string bogs and swamps. Central and western Labrador are located below tree line (Fig. 2A), but the highest hills are colonized by tundra vegetation. Low areas have an abundance of black spruce, caribou moss, and alders, which are preferentially located on wet grounds. Both regions are at the southern fringe of the zone of discontinuous permafrost.

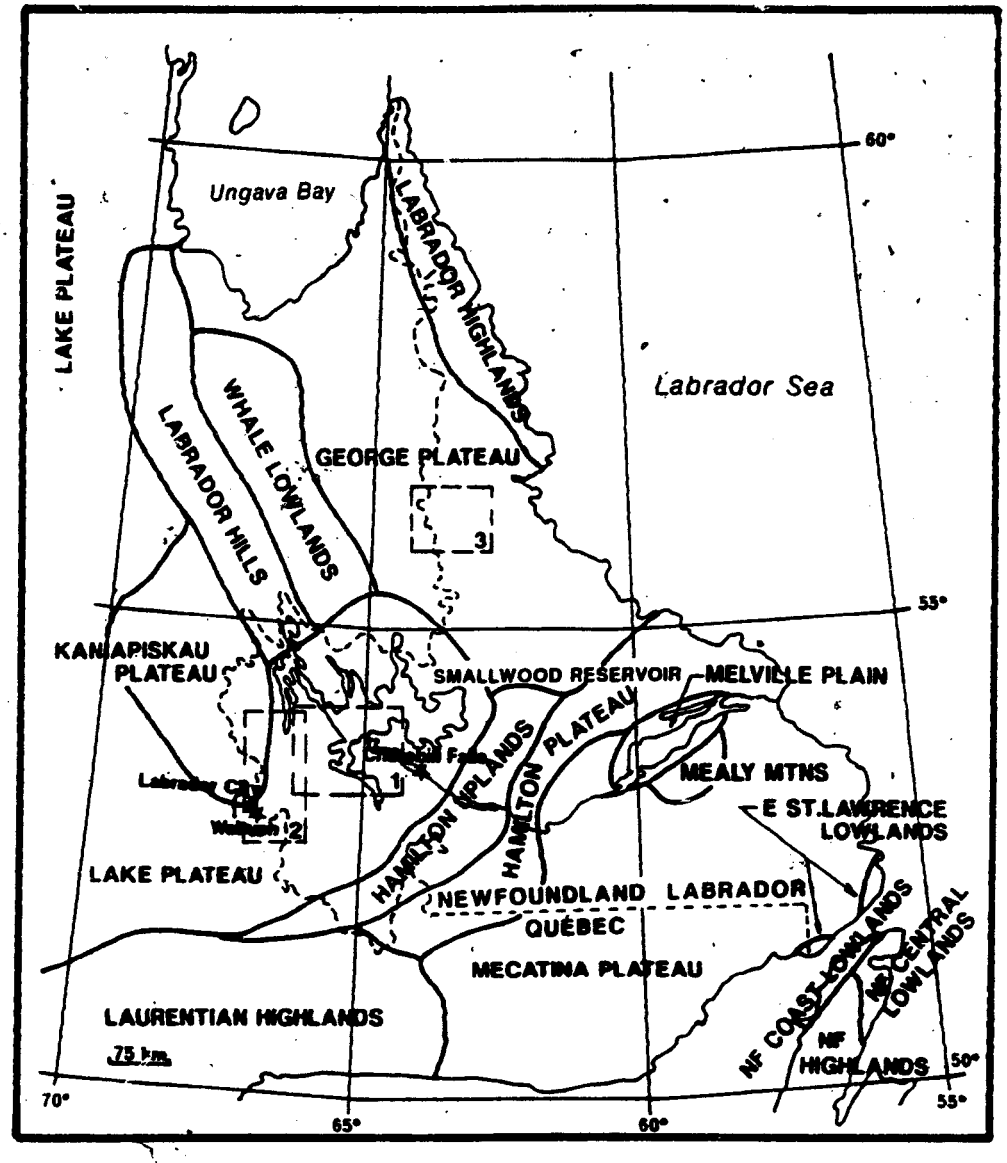
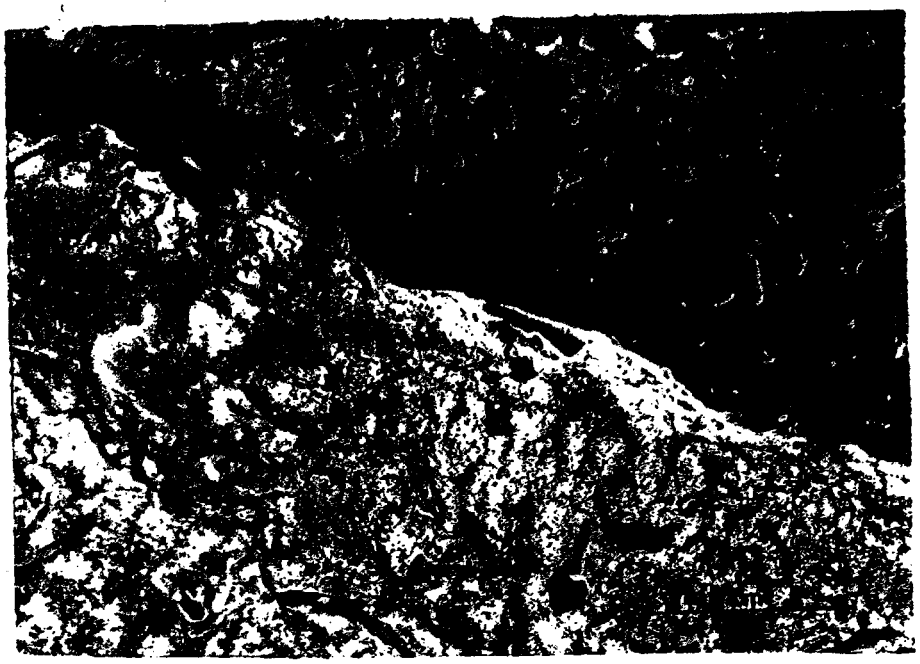
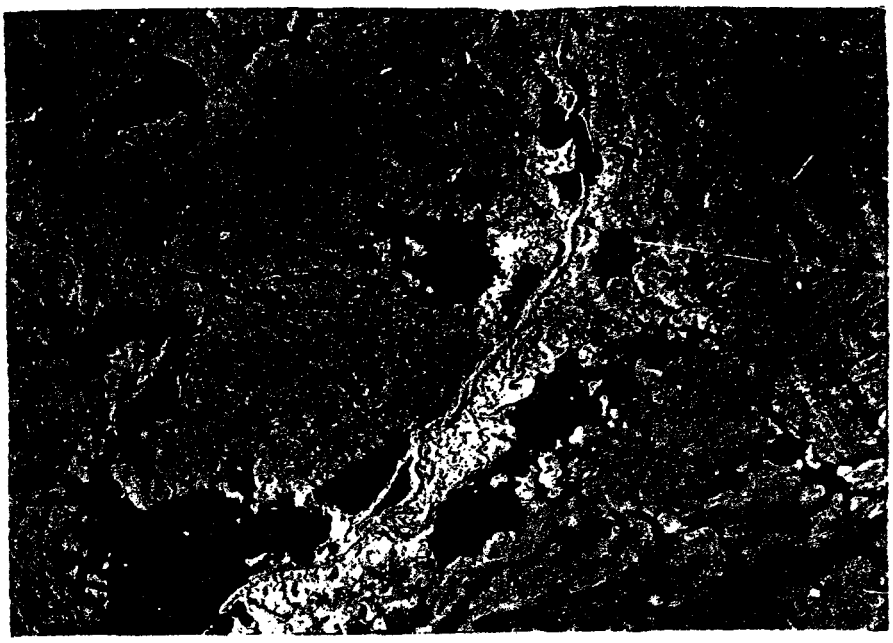


Figure 1. Physiography of Labrador and Nouveau Québec (from Bostock, 1967). Study areas (central (1), western (2) and northern (3) Labrador) are dashed in.



A



B

Figure 2. Terrain of the study areas. A) Central and western Labrador on the Lake Plateau (NAPL A12221-170; Gabbro esker). B) Northern Labrador on the George Plateau (NAPL A18290-60; Lac Brisson esker). The arrow points to the esker ridge on each photo. Also note the ribbed moraines (A) and fluted landforms (B).

Northern Labrador is located on a bedrock controlled plateau tilted up towards the east, the Nain-George Plateau of Greene (1974) or George Plateau of Bostock (1969). The region has an average elevation of 500 m asl, with local relief of up to 330 m near Lac Brisson (George River valley), and 500 m to the east. It is cut by deeply entrenched U-shaped valleys that trend east-west (Fraser River). Lac Brisson area straddles the regional watershed separating Ungava Bay and Labrador Sea. Lac Brisson area is above tree line and is underlain by discontinuous permafrost. The vegetation is composed of mosses and lichens, with a few dwarf trees located on protected, south facing slopes. Lakes and rivers are abundant in the area, and a few bogs are also present (Fig. 2B).

Bedrock geology

The bedrock of Labrador is composed of high grade metamorphic rocks and intrusive rocks, as well as of a cover of younger, less metamorphosed sedimentary and volcanic rocks of Precambrian age (Greene, 1970, 1974). There are also a few, small, isolated Cambrian and Triassic units. Labrador includes four Structural Provinces: the Grenville, Superior, Churchill and Nain provinces (Fig. 3) defined by structural trends, radiometric ages of metamorphic events, and degree of metamorphism.

Bedrock of the Superior Province underlies the northwestern corner of western Labrador, forming the Kaniapiskau Plateau, and is composed of granulite gneisses of the Ashuanipi Complex and acidic intrusive rock (Fig. 4A). The gneiss is well banded and pyroxene-bearing, intruded by pyroxene-bearing granodiorite and syenodiorite, as well as massive granites and quartz monzonite (Percival, 1987).

The southern region of western and central Labrador lies within the Grenville Province, including high grade metamorphic rocks of Neohelikian age subjected to deformation during the Grenvillian orogeny, and acidic, anorthosite and adamellite plutons. The southern metamorphosed part of the Labrador Trough, (i.e. the southern extension of the Kaniapiskau Supergroup, which includes all rocks of the Labrador Trough in the Churchill Province) includes schists, metadolomites, quartzites and iron formations of Aphebian age, and are intruded by Shabogamo Gabbro as well as granites and pegmatites.

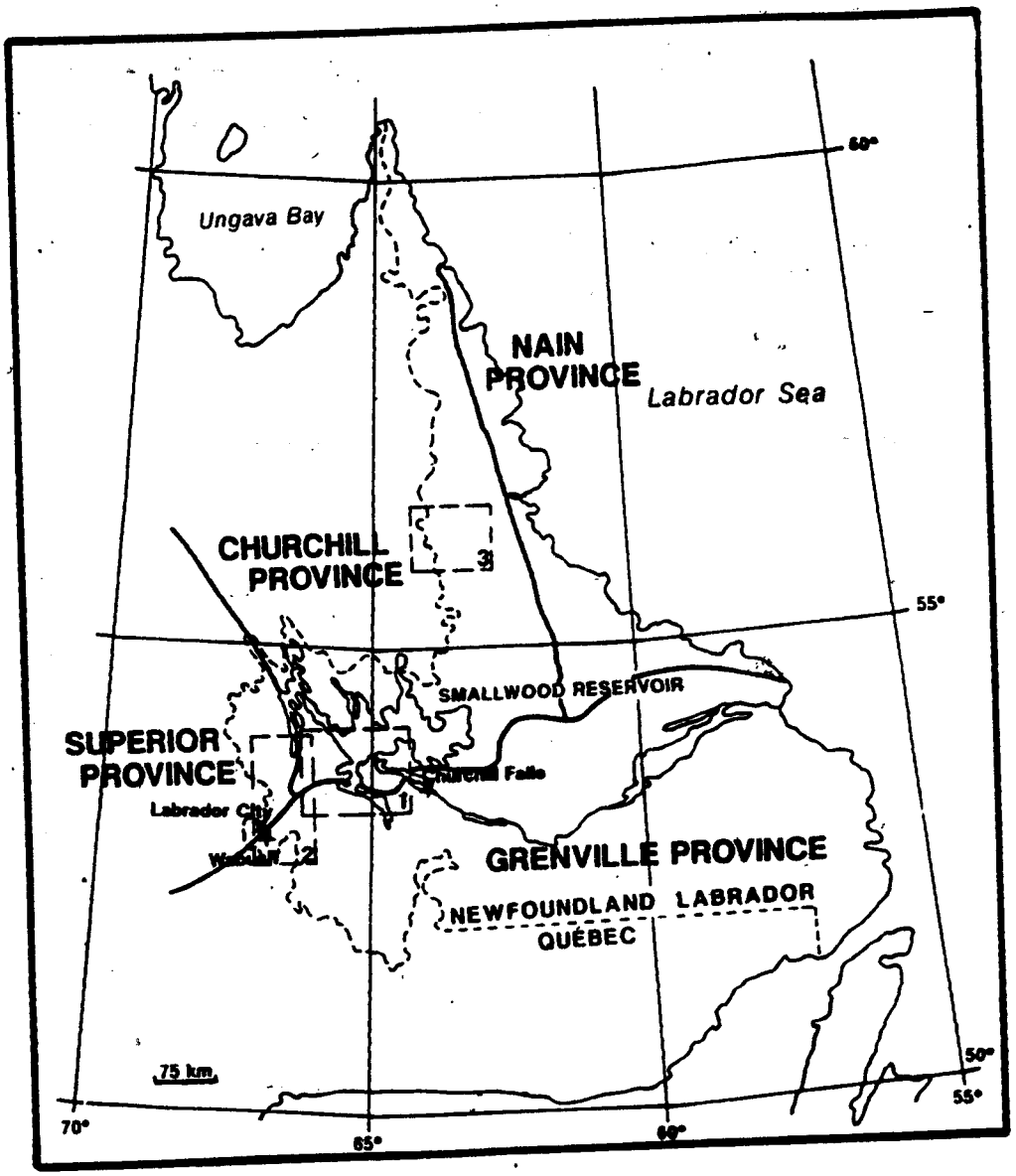
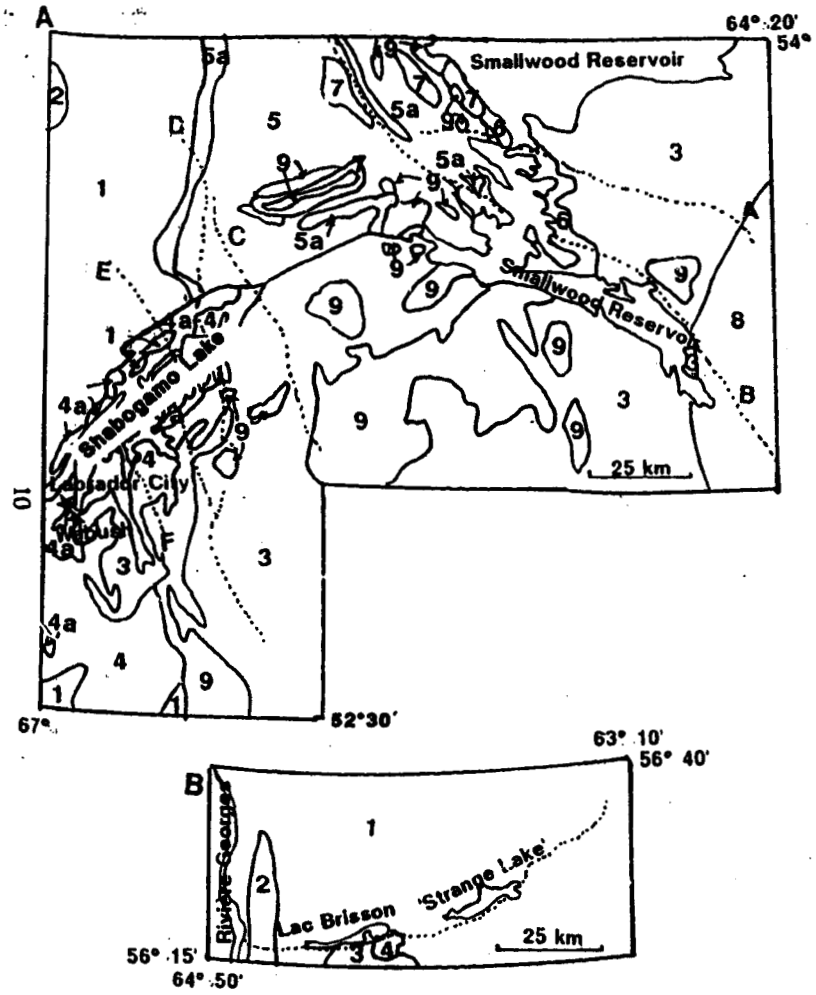


Figure 3. Structural provinces of Labrador and Nouveau Québec (from Greene, 1974). Study areas (central (1), western (2) and northern (3) Labrador) are dashed in.



PROTEROZOIC

Helikian and earlier

9 Mafic intrusive and metamorphic rocks, includes SHABOGAMO GABBRO

8 Paragneisses and granitoid gneisses

Paleohelikian

7 Quartzite, arkose and conglomerate of the SIMS FORMATION

Aphebian

KANIAPISKAU SUPERGROUP

6 Sedimentary and volcanic rocks of the BLUEBERRY LAKE FORMATION

5 Metasedimentary and metavolcanic rocks of the KNOB LAKE GROUP

5a Iron formation of the RUTH and SOKOMAN FORMATIONS

4 Metasedimentary and metavolcanic rocks of the KNOB LAKE GROUP south of the Grenville Front

4a Iron formation of the WABUSH FORMATION

Aphebian and earlier

3 Granulitic gneisses, amphibolites, schists

2 Felsic to intermediate intrusives

ARCHEAN

1 Pyroxene granulites and acidic intrusives of the ASHUANIPI COMPLEX

..... Eskers; A: Gabbro; B: Ossokmanuan; C: Ashuanipi; D: Shabogamo; E: De Mille; F: Moose Head

MIDDLE PROTEROZOIC

4 Strange Lake peralkaline granite

3 Hornblende quartz-monzonite

ARCHEAN AND LOWER PROTEROZOIC

2 Quartzite

1 Gneisses and granites, undifferentiated

..... Lac Brisson esker

Figure 4. Bedrock geology. A) Bedrock geology of central and western Labrador (from Greene, 1970; and Rivers, 1985), and part of Nouveau Québec (from Avramtchev, 1985). B) Bedrock geology of northern Labrador and part of Nouveau Québec (from Taylor, 1975a; 1975b; 1975c; and Miller, 1986; 1988, pers. comm.).

In the northern part of western and central Labrador, bedrock of the Churchill Province is less metamorphosed than south of the Grenville Front. The bedrock includes Aphebian sedimentary and volcanic sequences of the Kaniapiskau Supergroup comprising the Labrador Trough, and high grade metamorphic rocks and unmetamorphosed anorthositic and acidic plutons to the east of the Labrador Trough comprising the Eastern Basement Metamorphic Complex (Wardle, 1981). Some of the rocks of the Churchill Province are of Helikian age, such as the supracrustal Sims Formation, which comprises a pink quartzite and a red arkose, located at the eastern edge of the Labrador Trough. Shabogamo Gabbro and various acidic intrusives, also of Helikian age, are found in the Trough and east of it.

In northern Labrador, bedrock of the Churchill Province is composed mainly of high grade quartzo-feldspathic gneisses intruded by various late plutons of quartz-monzonite composition, as well as by a highly differentiated granite, the Strange Lake peralkaline granite (Fig. 4B). A unit of quartzite is located west of Lac Brisson. The quartzite and the gneisses are of Archean to Lower Proterozoic age, while the intrusive rocks are of Middle Proterozoic age.

Indicator lithologies, easily identified and traced in glacial and fluvioglacial sediments to their limited and well defined outcrop area, are used to evaluate both distance and direction of transport. Where an indicator lithology crops out over a large area, tracing of debris outside of the outcrop area provides a basis for estimating minimum distance of transport. Indicator rocks used in this study are, in central and western Labrador, quartzites and arkoses of the Sims Formation, volcanic rocks of the Blueberry Lake Group, slates of the Knob Lake Group, and iron formation of the Ruth, Sokoman and Wabush Formations (respectively units 7, 6, 5 & 4, and 5a & 4a, on Fig. 4A), and in northern Labrador, the Strange Lake peralkaline granite, a hornblende quartz-monzonite, and a quartzite, both unnamed (respectively units 4, 3, and 2, on Fig. 4B) (Appendix II).

Surficial geology

Surficial deposits exist over virtually all of the Labrador Peninsula, although some areas only have a partial cover. Most glacial landforms and deposits are believed to have been developed during

the last, or Classical Wisconsinan glaciation. Only upon studying small scale erosion features and glacial dispersal patterns (Klassen and Bolduc, 1984, 1986; Bolduc, 1985; Thompson and Klassen, 1986; Klassen and Thompson, 1987, 1988) does it become evident that the geological record of glacial history in Labrador relates in part to pre-Late Wisconsinan events.

Glaciations

The first mention of glacial geology on the peninsula can be found in Low's (1896) extensive report of expeditions down the main rivers of Labrador during the summers of 1893, 1894 and 1895. He recognized a major centre of ice accumulation in Labrador and central Québec by striae measurements. Since then, work based on tilt of proglacial lake shores provided evidence for a residual ice centre located in the area of the Labrador Trough, near Schefferville (Barnett and Peterson, 1966) (Fig. 5). Work done in the periphery of the ice sheet however, may not be valid to reconstruct the location of an ice accumulation centre (Henderson, 1959).

Most of the work undertaken after Low on the Labrador glaciations was restricted to the Torngat Mountains, until some of the interior became more accessible with the building of the Québec North Shore and Labrador Railway in the mid 1950's. Work in the Torngat Mountains yielded the recognition of three major glacial events, based on weathering differences among topographic zones separated by lateral moraines (Ives, 1957), named «Komaktorvik», «Koroksoak» and «Saglek», and interpreted as Early to Middle Pleistocene («Komaktorvik» and «Koroksoak» glaciations) and Classical Wisconsinan («Saglek») (Vincent, 1989). The earliest, and most extensive glaciation was the Komaktorvik Glaciation, which completely covered the Torngat Mountains, except for the highest summits. The second glaciation, the Koroksoak Glaciation, was less extensive than the Kómaktorvik Glaciation, as the Torngat Mountains were nunataks, while the southern hills were completely covered. Finally, the third or Saglek Glaciation, corresponds to what has been defined as the upper limit of the Labradorean Sector of the Laurentide Ice Sheet in the Torngat Mountains (Prest, 1984). During the Saglek Glaciation, the Torngat, Kaumajet, Kiglapait and Mealy mountains were all nunataks. The centre of radial outflow and of maximum ice thickness at this time was located

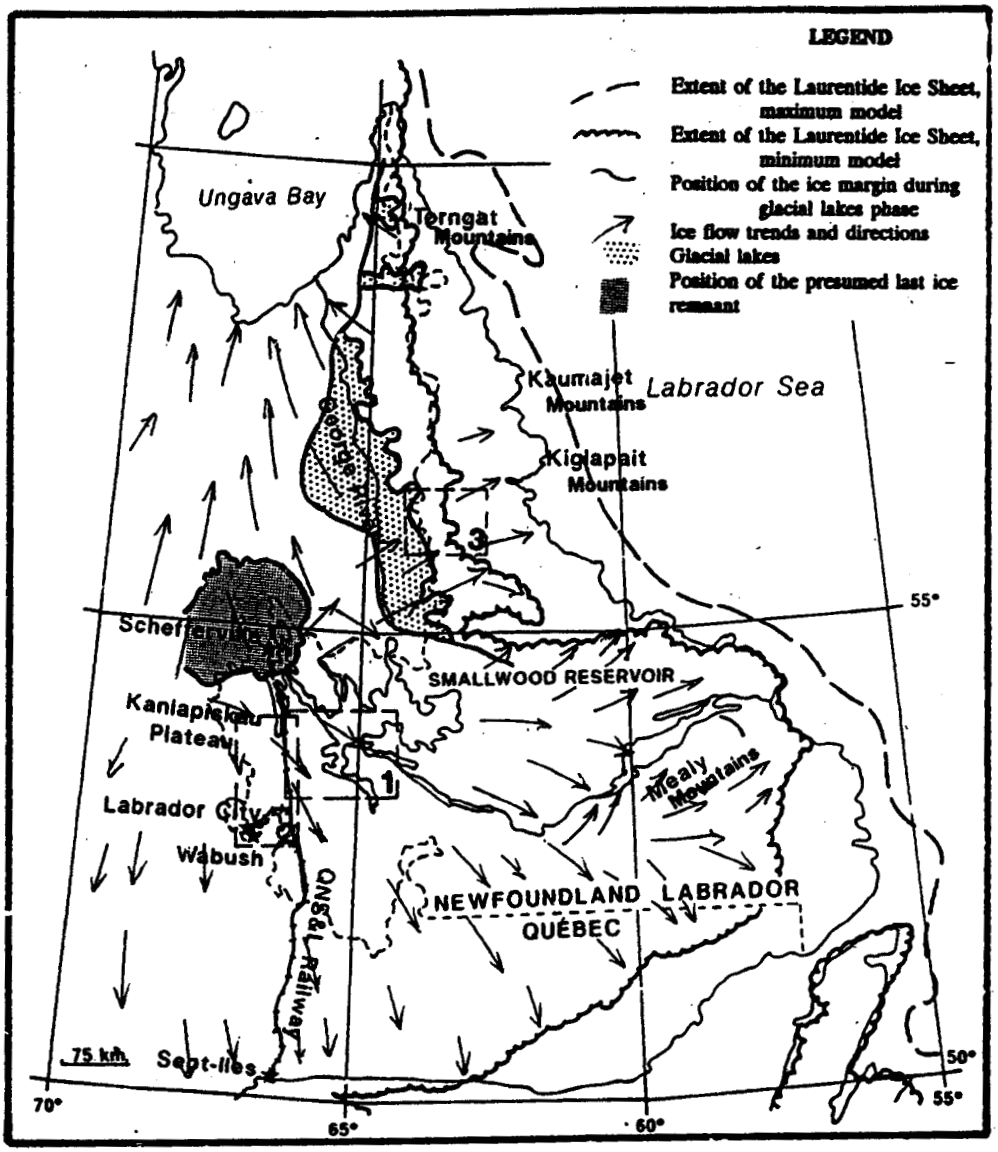


Figure 5. Surficial geology of Labrador and part of Nouveau Québec (from Greene, 1974; Prest, 1984; Dyke and Prest, 1987). Study areas (central (1), western (2) and northern (3) Labrador) are dashed in.

on the Kaniapiskau Plateau (Fig. 5).

The Torngat Mountains have been identified as the location of initial build-up of snow and ice at the beginning of the glacial epochs (Flint, 1943). The lowering of the snow line however, as must have happened as the climate deteriorated, would allow snow and ice to accumulate in the interior plateau and spread radially from it (Henderson, 1959; Dyke *et al*; 1989). No arguments were made for or against a migration of the ice centre towards Hudson Bay, where it was believed that the maximum thickness of ice was located during the Wisconsinan maximum (Henderson, 1959). The evidence that Henderson (1959) found all pointed to the presence of an ice dispersal centre in Labrador-Nouveau Québec.

On the basis of glacial striae and dispersal of distinctive erratics, both Henderson (1959) and Hughes (1964) argued for more than one ice flow direction in central-eastern Québec. Areas north of Schefferville however, appear to have only recorded the latest ice flow, to the north-east. In central Labrador, based on the truncated radial pattern of drumlins, two sets of striae, and transport of Labrador Trough rocks 105 km west of the Trough, two flow events, the first one to the WSW and the later one to the NNW, were reported (Hughes, 1964). Most of the landforms are not topographically controlled, indicating that the movement occurred when the ice was thick enough that it was not affected by the hills and valleys in the area.

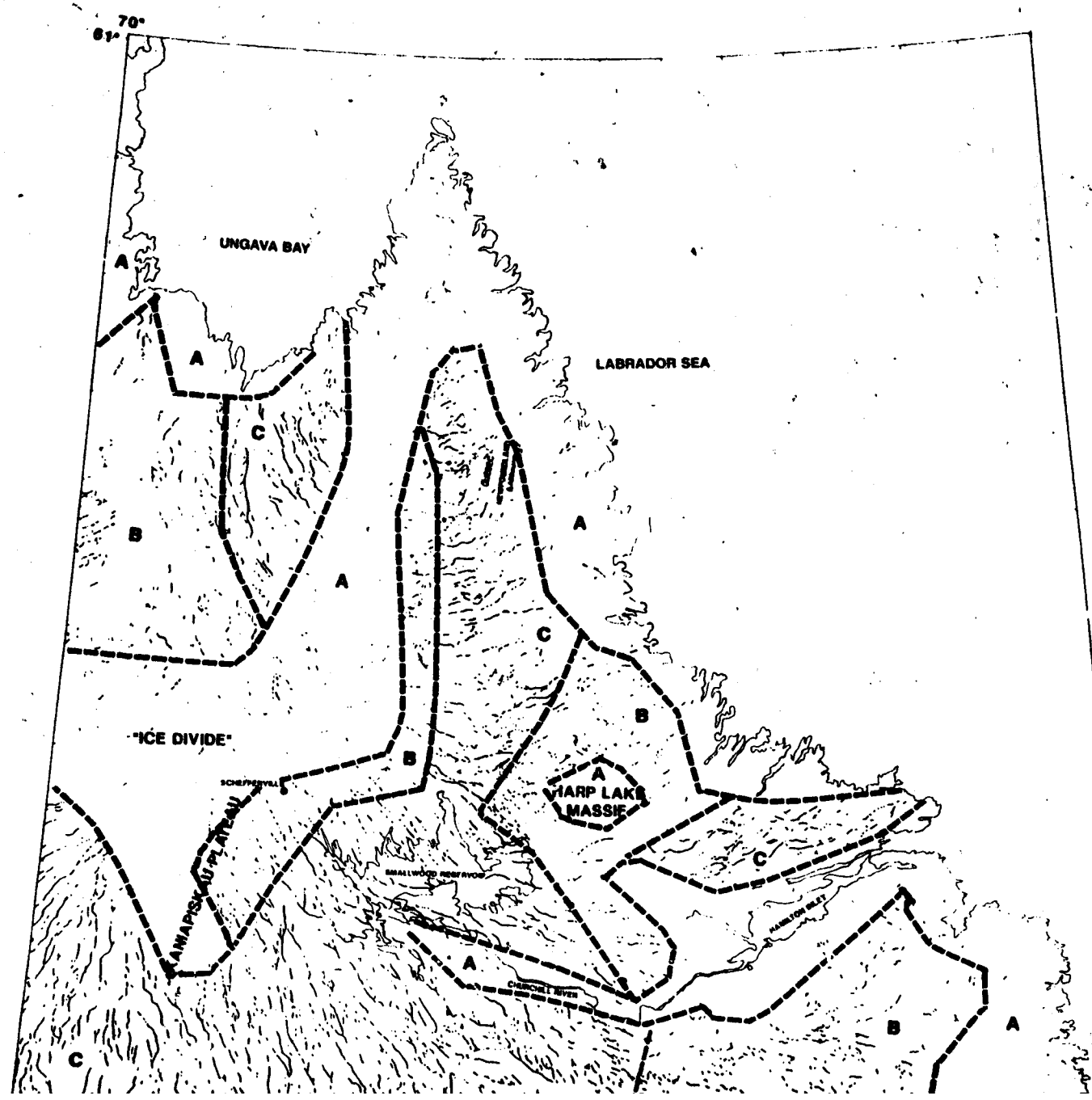
Henderson (1959), who worked along the Québec North Shore and Labrador Railway corridor, also documented two ice flow directions. The oldest was to the south-east and south, and the second one was to the north-east. This last one, however, was not found in the centre of his area. Henderson's map (1959) indicated both an older and a youngest northeast flow in the Schefferville area. Recent studies of striae document ice flow events of distinct trends and ages in central (Klassen and Bolduc, 1984; Thompson and Klassen, 1986) and western Labrador (Klassen and Thompson, 1987). Two ages of northeast flow have been identified, although the second of the last is not prominently inscribed on bedrock. A regional flow to the northeast appears to have occurred prior to the final south-east flow that moulded most of central Labrador. The southeast flow appears to

have been a late, localized ice stream flowing from the central Labrador Trough to the south-east, most likely draining the ice sheet through Lake Melville and to the Labrador Coast (Klassen and Thompson, 1987).

An ice divide has been recognized in central Labrador-Ungava, largely on the basis of landforms, and has been described as U-shaped. The dynamic history of the ice divide has been proposed (Dyke and Prest, 1987), but the geologic basis for ice sheet modelling, however, remains sketchy. In the context of this dissertation, the general position of the centre during the last part of the glaciation, prior to the formation of eskers, was over Nouveau Québec, likely northwest of Schefferville, as eskers radiate away from that area. The position of Lac Brisson esker and others in northern Labrador indicate that the ice divide was located west of George River, at least during their formation, which is where the 10 ka paleogeographic reconstructions of Dyke and Prest (1987) places it. The 10 ka position of the ice margin in Labrador (Dyke and Prest, 1987), (7.5-7.7 ka (Clark & Fitzhugh, 1990)) roughly corresponds to the limit between the zones where few eskers are located, and where esker systems which form an elongate dendritic drainage pattern are found (Fig. 6).

Glacial stratigraphy

Stratigraphy, or the lack thereof, has always been a problem in this sector of the Laurentide Ice Sheet. It is believed that surficial sediments in Labrador have been deposited during the last glacial events, and organic material should be about 8,000 yrs BP or younger. «Old» wood (^{14}C date of 24,250 ± 600 yrs BP) had been reported near Schefferville (Granberg and Krishnan, 1984), as well as anomalously old ^{14}C dates (ranging from 9,980 ± 40 yrs BP to 16,975 ± 1,040 yrs BP, (Stravers, 1980) a time during which the area should have been under a thick cover of ice), but most of the dates have been questioned because of suspected contamination. Klassen and Thompson (1987, 1988) report a stratigraphic sequence from Wabush which includes at least two tills of differing character, as well as intertill fluvioglacial and lake sediments, all of which are of Pleistocene age. Wood (Picea) collected from the lake sediments gave a >50,000 yrs BP ^{14}C date, and seem to indicate a climate much warmer than today's. Seeds of a pre-Sangamonian species, Aracites (Aracispermum) which


70°
61°
UNGAVA BAY
LABRADOR SEA
"ICE DIVIDE"
SCHEFFERVILLE
KANAPISKAU PLATEAU
HARP LAKE
MASSIE
SMALLWOOD RESERVOIR
CHURCHILL RIVER
HAMILTON INLET
A
B
C

occurs within Late Tertiary deposits in Arctic Canada and Lower Pleistocene deposits in Scandinavia have also been identified (Klassen and Thompson, 1988). More work is required before the glacial stratigraphy of Labrador is unravelled.

Deglaciation

Evidence for ice movements and deglacial landforms mostly relate to the Late Wisconsinan events. Two reconstruction of the Laurentide Ice Sheet during Late Wisconsin place the ice sheet margin either in the Labrador Sea (maximum) or inland of the Labrador coast (minimum (Prest, 1984). By 12 ka, the margin of Laurentide Ice Sheet had reached the coasts (Dyke and Prest, 1987; Vincent, 1989), where it may have stayed for a long time, as Clark and Fitzhugh (1990) place the 7.5-7.7 ka ice margin just inland from the coast. Deglaciation proceeded through three stages (Greene, 1974; King, 1985). First, the retreat of the outlet glaciers in the Torngat Mountains occurred. This was followed by a proglacial lake stage, where lakes were dammed up against the regional watershed as the glaciers retreated to the north, blocking drainage through Ungava Bay. Glacial Lakes Naskaupi I and II and McLean I and II (Ives, 1960), located along George River and Whale River, were amongst the largest proglacial lakes, and left the most prominent shore lines. Other lakes were located in the Torngat Mountains (Ives, 1957), and in the area of Wabush-Labrador City (Harrison, 1963). The close association between eskers and drumlins (Vincent, 1989), and the patterns of striae and dispersal of erratics (Klassen and Thompson, 1989), indicate that the ice sheet was active during most of the deglaciation. Based on the pattern of fluvioglacial deposits and meltwater channels, it has been proposed that final deglaciation of residual ice masses occurred in the Schefferville area through general stagnation of a residual ice mass in a warming climate (Derbyshire, 1962).

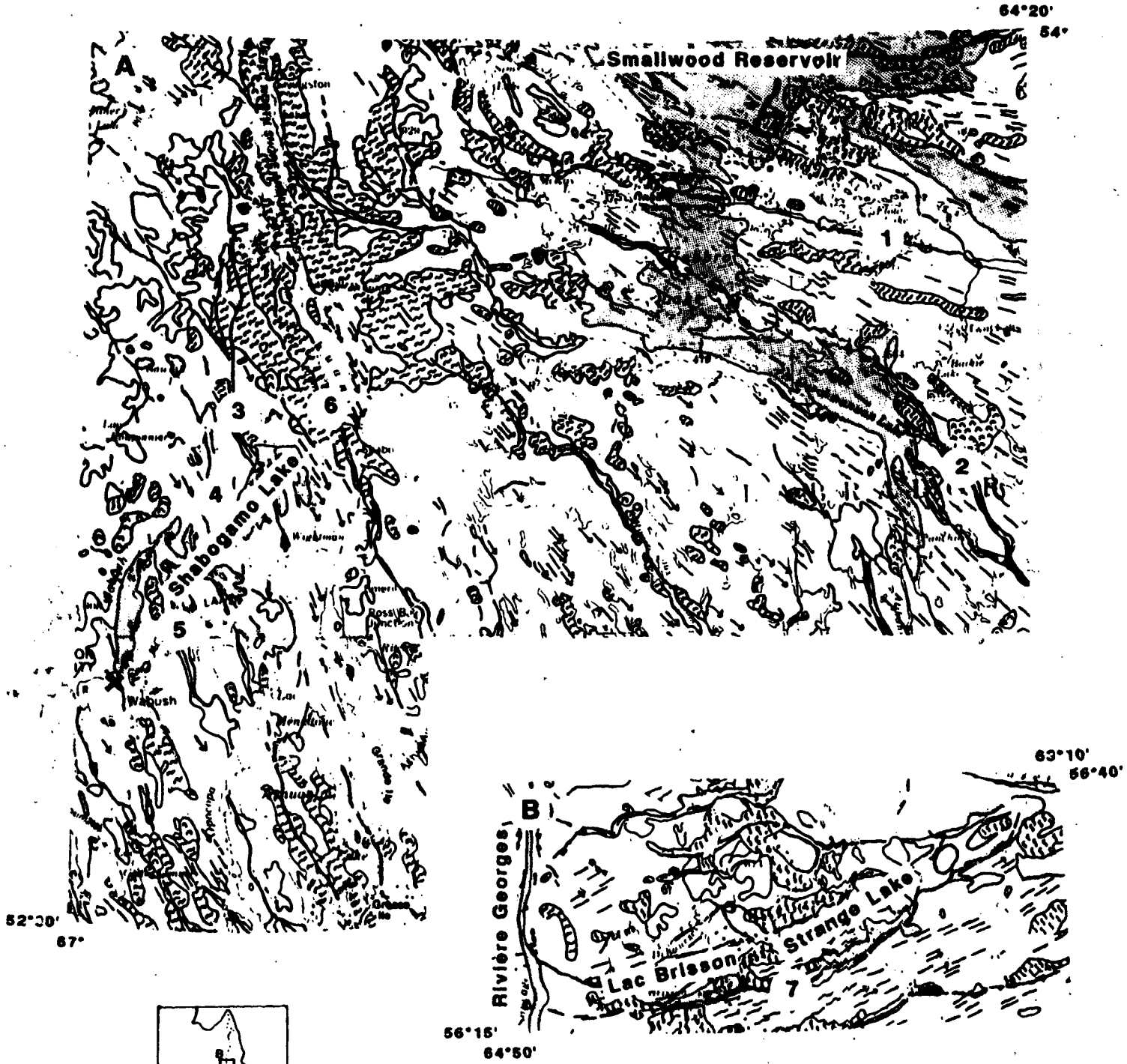
In the George River area, eskers originate west of the George River valley, in the area of the presumed ice divide, and trend eastward, directly across George River valley and the regional watershed, a climb up the valley side of about 150 m, and extend across the eastern plateau, demonstrating meltwater drainage to the Labrador Sea. The emplacement of the eskers, some of which are over 125 km long, had to occur prior to development of major glacial lakes within that

valley. Recent work by Klassen and Thompson (1988; Klassen, pers. comm., 1989) indicates that the lakes may have been a late feature, and that they were controlled by an ice mass retreating north, clockwise around a pinning point at the northern tip of Labrador (Dyke and Prest, 1987). If the re-evaluation of Clark & Fitzhugh (1990) for the timing of glacial lake Naskaupi is correct, then there was about 500 years for ice retreat to occur between the Labrador Coast and the position of the ice margin during the glacial lakes event. During the formation of the esker segments crossing the George River valley, the ice sheet had to be >1500 m thick and the ice margin >100 km away (see p. 75 for calculations) for the ice surface gradient to control the direction of flow of basal meltwaters and sediments across the valley rather then ponding the water in a subglacial cavity over the valley.

Glacial deposits

Glacial deposits in Labrador have been mapped on a reconnaissance basis using air photos with limited ground checks over the whole peninsula (Douglas and Drummond, 1955; Vanderveer, 1973; Fulton, Hodgson and Mining, 1978, 1979a to f; Fulton and Hodgson, 1979; Fulton, Hodgson, Mining and Thomas, 1979a, 1979b; Fulton, Hodgson, Thomas and Mining, 1979; Fulton and Mining, 1979; Fulton, 1986a, 1986b; Bolduc, 1985; Klassen *et al*, in prep.). A few small areas, usually the target of detailed mineral exploration programs, have been mapped in detail (eg. Morrison, 1966, in the Churchill Falls area; Batterson, 1989, for the Strange Lake area). The main glacial features of the Labrador Peninsula are the abundant drumlin fields, areas of ribbed moraine, and large esker systems over the whole area, except in the interior, where an area of relatively few landforms and thin drift appears to outline an oval-shaped «ice divide». The paucity of end moraines, especially in the interior, is an outstanding characteristic of the Peninsula. The close association between eskers and drumlins, as well as the lack of widespread hummocky moraine in the area lends support to a wet based retreating ice sheet experiencing basal flow (Dyke and Prest, 1987).

Glacial deposits in the three study areas (Fig. 7) are attributed to the action of the late-Wisconsin glaciers. Most of the area is covered by till, which is drumlinized and has extensive areas of ribbed moraine. The orientation of the drumlins and of the ribbed moraine trains indicates ice


64°20'
54°
A
Smallwood Reservoir
1
2
3
4
5
6
Shabogamo Lake
Wabush
52°30'
67°
63°10'
56°40'
B
Rivière Georges
Lac Brisson
Strange Lake
7
56°15'
64°50'

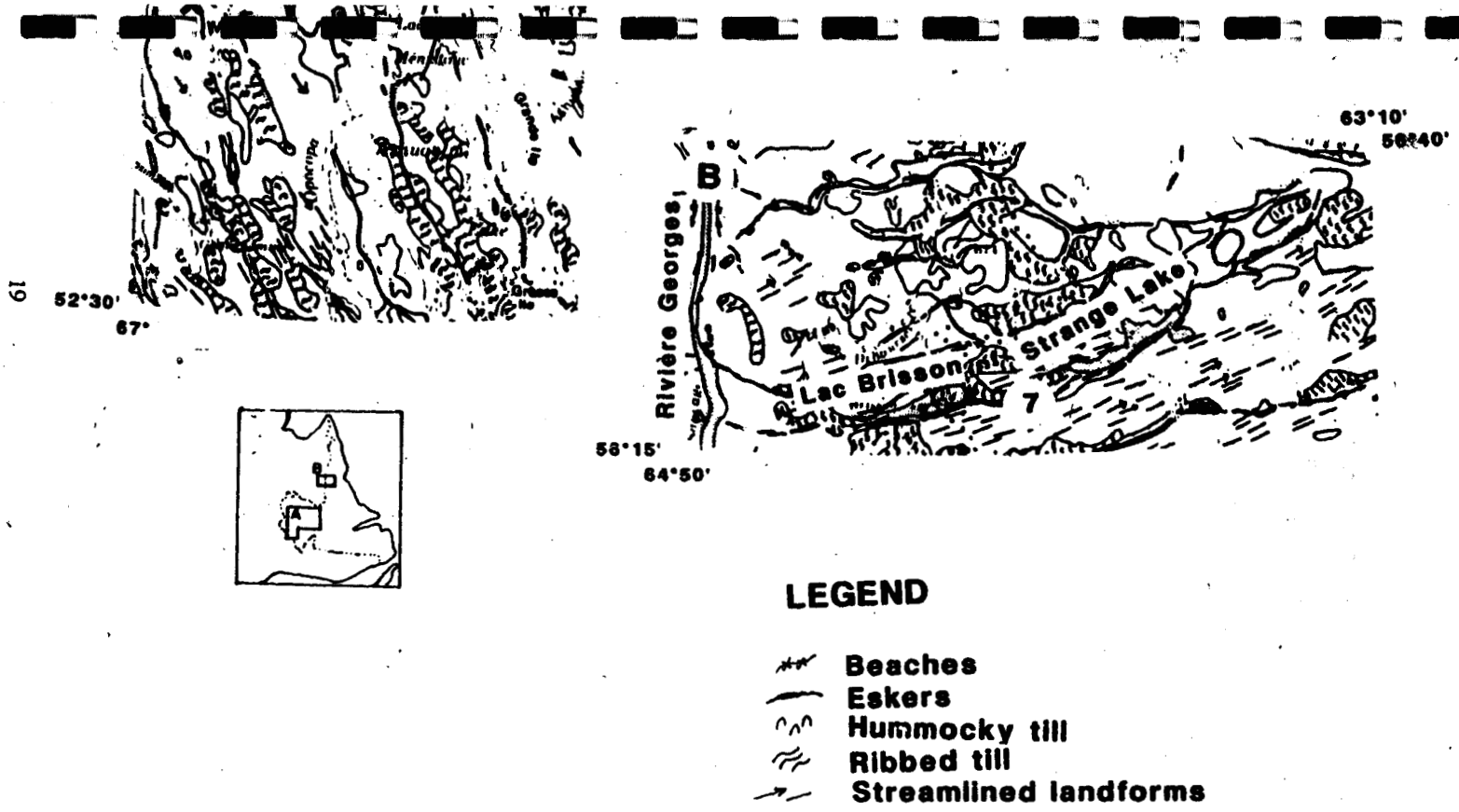


Figure 7. Generalized surficial geology from air photo interpretation for the three study areas. A) Central and western Labrador B) Northern Labrador. Eskers under study are 1) Gabbro esker 2) Ossokmanuan esker 3) Shabogamo esker 4) De Mille esker 5) Moose Head esker 6) Ashuanipi esker 7) Lac Brisson esker

From Klassen *et al*, in prep.

flow towards the south-southeast, in central and western Labrador, and towards the northeast in northern Labrador.

PREVIOUS LITERATURE

The distribution of eskers in Canada is restricted to south of the 72° latitude, suggesting the need for a temperate (warm based) glacier and rapid ablation for the formation of eskers (Banerjee and McDonald, 1975). Longer, integrated esker systems seem related to temperate glaciers, whereas short and scarce eskers have been attributed to polar conditions (Ringrose, 1982). Esker characteristics, distribution, morphology, stratigraphy, and lithologic composition, as well as esker origin, supraglacial or subglacial, have been discussed in many papers, and will be presented in this section. A brief review of meltwater production and debris availability, however, needs to be presented first, for both are needed to construct eskers.

Meltwater production

Meltwater can be produced at the glacier surface by solar heat and thermal convection of air across the surface, within the glacier by heat generated by ice flow, and at the glacier base by geothermal heat, ice flow and pressure melting. Over polar ice sheets, surface melting, surface runoff and rain are only minor contributors of meltwater, while in a temperate glacier, surface meltwater can be at least one order of magnitude more important than basal meltwater (Shreve, 1972).

The production of meltwater at the surface of the glacier is controlled by annual and diurnal cycles, and occurs mainly during summer. Precipitation as rain is important in the total amount of surface water discharged by a glacier (Haakensen and Wold, 1981). Surface meltwater, however, is important in the formation of eskers only if it reaches the subglacial drainage system. Surface meltwater can percolate through the snow and firn along grain boundaries and by way of a network of channels which coalesce with increasing depth to form a vertical drainage network (Shreve, 1972). The firn/ice boundary, because of the relative impermeability of the ice, acts as a barrier to further vertical flow (Drewry, 1986; p. 22-23). The surface meltwater that percolates to the firn/ice boundary is discharged through high-level englacial tunnels until, near the terminus of the glacier, the high-level

englacial conduits may connect with the subglacial system via moulins (Fig. 8; Collins, 1977 *in* Drewry, 1986; p. 23).

Englacial meltwater is found in low concentration throughout the glacier, and tends to increase near the base of the glacier (Sugden and John, 1976; pp. 19-23; 281). It contributes approximately 0.01 to 0.02 m/yr/unit area of water in most glaciers, but could be up to 0.4 m/yr/unit area if the sliding velocity of the glacier is up to 2 km/yr (Drewry, 1986; p. 21). Englacial meltwater percolates downward through either intergranular veins and capillaries, or in cracks, fissures and moulins (Nye and Frank, 1973; Drewry, 1986; p. 23), the last three being more efficient in carrying englacial meltwater downward to the basal system (Fig. 8). The number of conduits decreases downward, but their size increases (Drewry, 1986; p. 23). The larger passages tend to get bigger, while the smaller ones are abandoned (Shreve, 1972). From radar and dye work, as well as from theoretical considerations, there are few extensive subhorizontal networks of englacial channels (Drewry, 1986; p. 23). Due to the size of the Laurentide Ice Sheet, even though englacial meltwater was likely present at low concentration, it probably contributed a large amount of water to the system, and presumably to subglacial meltwater discharge.

Basal meltwater production is estimated to about 10 mm/yr/unit area (Shreve, 1972), to 30 mm/yr/unit area (Drewry, 1986; p. 21) and up to 60 mm/yr/unit area (Sugden and John, 1976; p. 281). At the base of the glacier, water is present as a sheet of various thickness (a few mm, Weertman, 1966; 1972; Walder, 1982; to several tens of meters, Shaw and Kvill, 1984; Shaw, 1983; 1989), or in conduits of various shapes and sizes. Water may also be ponded beneath the ice sheet in lakes varying from a few square kilometres to up to 8,000 km^2 (Drewry, 1986; p. 29).

The basal meltwater system

Water at the base of a glacier flows in the direction of surface slope of the glacier if the bed is level (Shreve, 1972). Over an uneven bed, if the subglacial topography is completely buried by ice, water also flows in the overall direction of surface slope of the glacier, but follows valley floors and

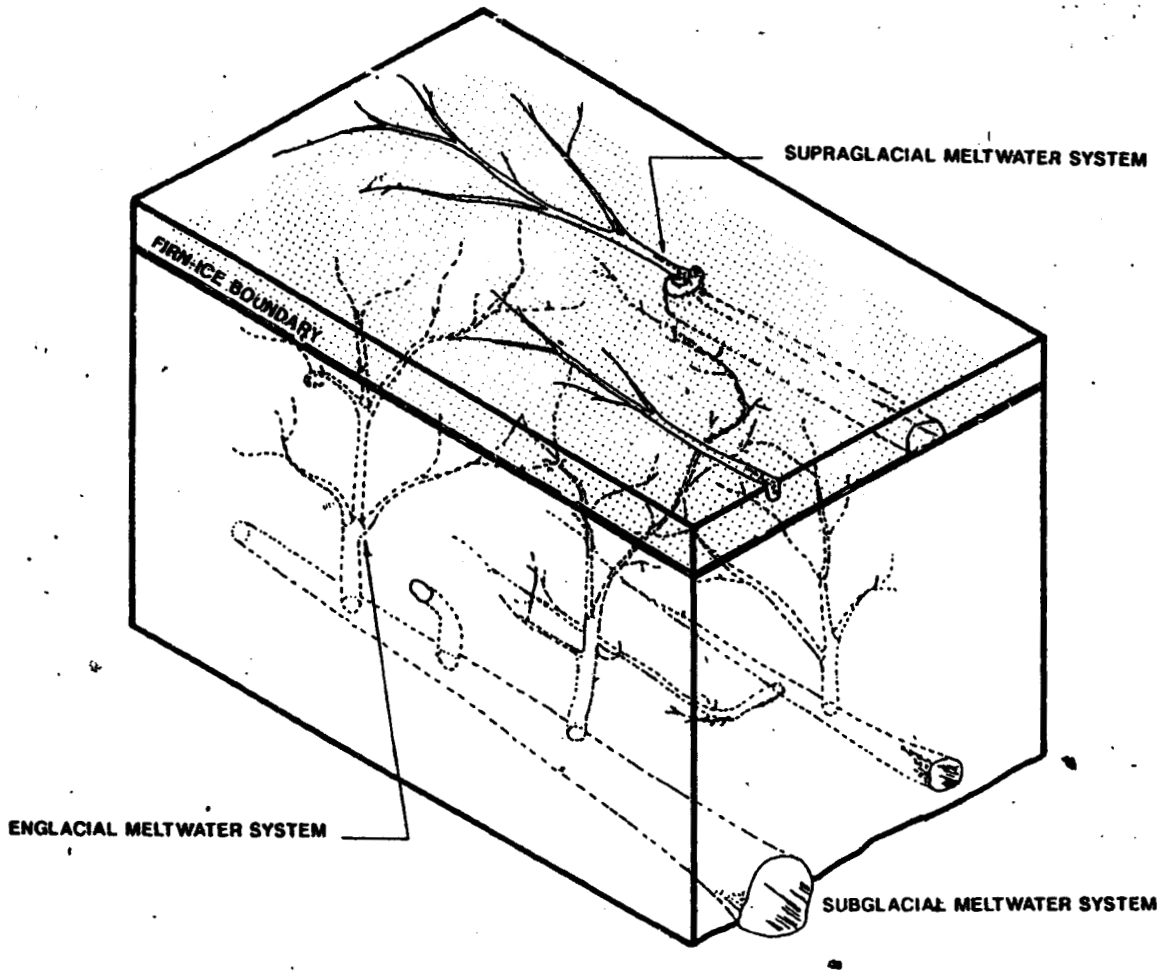


Figure 8. Meltwater passages in a hypothetical ice sheet. Away from the ice margin, the lower limit of the supraglacial meltwater system is the firn/ice boundary, which is somewhat impermeable. Close to the ice margin, moulins may connect with the subglacial drainage system.

meltwater descending to the base, as well as to passage constrictions (Price, 1973, p. 141), can drive the water up-hill (Carey and Ahmad, 1961; Shreve, 1972). The steeper the ice surface, the less topography influences the esker path (Shreve, 1972).

In a subglacial system, the size of a tunnel may change due to a difference in the time response of frictional melting of the tunnel triggered by an increase in meltwater drainage (on the order of hours to days), and ice creep, which tends to close the tunnel in response to low pressures resulting from a lower discharge event (on the order of weeks) (Shreve, 1972; Drewry, 1986; p. 20). Tunnel size is not significantly affected by short-term fluctuations (diurnal cycle), but adjusts to longer term cycles (seasonal cycles), with a response time of weeks (Shreve, 1972). Therefore, as has been documented in modern glaciers (Arnborg, 1955), the tunnels enlarge rapidly in response to a high discharge event (Matthews, 1973) such as spring thaw, but may not close entirely during the next fall and winter, especially if there is residual flow. A tunnel may thus be reutilized the following year. Dry tunnels can remain intact for periods longer than a year especially if the rate of movement of the ice sheet is slow (Mannerfelt, 1981). Tunnel closing rates also depend on the difference between overburden and water pressures (Rothlisberger, 1972) such that higher tunnels, or tunnels under a thin ice sheet take longer to close.

The most favourable conditions for the formation of large, but not necessarily long, eskers is a large subglacial meltwater discharge and a low ice surface gradient (Shreve, 1972) coupled with a large debris source, such as would be found at the base of a stagnating, or nearly stagnating ice sheet. Long eskers appear to be the result of the up-ice migration of the stagnant marginal zone and its associated tunnel system (Price, 1973, p. 141), so long as the formation of the tunnels is restricted to that stagnant zone.

Debris production

Without debris, meltwater cannot build eskers or other fluvioglacial landforms. In modern glaciers, other than mountain glaciers, the basal 10-20 m of the ice appear to be the only part carrying a significant amount of debris (Shilts, 1984). Studies of the Matanuska glacier in Alaska also indicate

that the most debris-rich part of the glacier is the stratified facies of the basal zone, which is up to 74% debris by volume (Lawson, 1979). A literature-based study of the amount of debris in a temperate glacier by Pessl and Frederick (1981) estimates debris-rich ice to be only 40-55% debris by volume.

An ice sheet 1500-2000 m thick, such as the one that covered Labrador (CLIMAP, 1976), over an area with maximum local relief of approximately 500 m, would not be expected to have any significant amount of supraglacial debris. Englacial debris bands (medial moraines) corresponding to localized higher topography can be expected, but could only be tapped as a source of debris for the esker systems if they were intersected by a meltwater conduit.

Esker debris must therefore be primarily of subglacial origin, derived from either debris-rich basal ice or glacial sediments, or both, implying that the esker-forming stream was located at, or regularly intersected, the base of the ice sheet. A secondary source of debris entrained by subglacial meltwaters is debris derived directly from bedrock by subglacial mechanical erosion (crushing and abrasion), as well as, to a lesser degree, mechanical and chemical erosion by meltwater itself of the underlying substrate (Drewry, 1986, p. 89), and erosion of pre-glacial sediments.

There is insufficient sediment within an esker-equivalent volume of glacier ice to form an esker (Shilts, 1984). Basal glacial sediments may be melted out of the tunnel ice walls, especially during high flow events such as spring thaw, contributing to the meltwater stream coarse and fine load (Drewry, 1986, p. 147). As ice creep redirects ice and its basal debris load towards an esker-forming tunnel, more material becomes available for further erosion by the subglacial stream. The debris in an esker tunnel is thus brought in by ice moving in the direction of ice flow, ice creep towards the tunnel, and fluvioglacial erosion (Shilts, 1984; Fig. 9). Fine material may also be brought in by Weertman films. Where both supraglacial and englacial debris are present, they may contribute to esker debris if they are tapped by a meltwater stream connecting to the subglacial system.

Esker characteristics

While eskers are characteristics of glaciated terrain, regional studies are few (Stoelting, 1978;

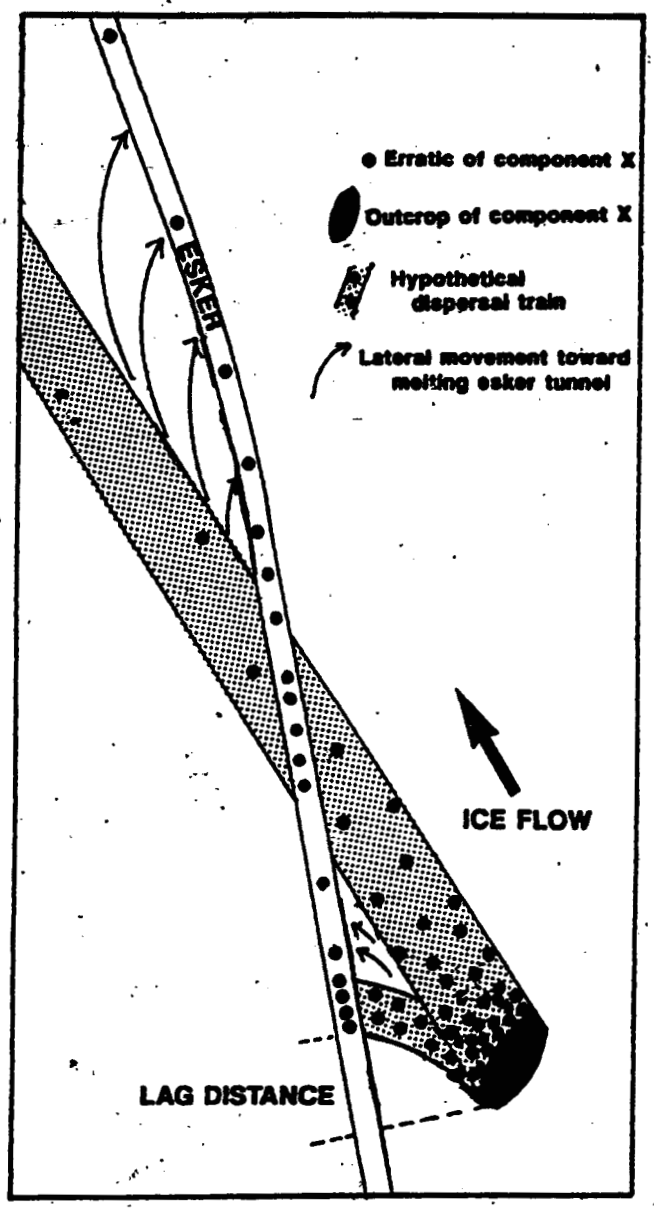


Figure 9. Entrainment of debris in an esker tunnel. Incorporation of clasts of component «X» in an esker is by direct and indirect glacial transport, followed by fluvioglacial transport. In this example, there is no direct fluvioglacial erosion of component «X».
(Modified from Shilts, 1984)

Ringrose, 1982; Aylsworth and Shilts, 1990). Most esker studies were conducted on small portions of eskers, and even though a series of esker characteristics can be established that relate an esker segment to the region where it is located, an overall unified description is difficult to make. This section will review typical esker characteristics as described in the literature.

Distribution

Eskers, and glacial landforms, generally are not characteristic of regions of ice divides, but are widespread in Maine, Labrador-Ungava, Keewatin and Scandinavia, in areas near to, and centred around, the residual ice masses (Fig. 6). The relative absence of meltwater in areas of divides (Lauriol and Gray, 1987) may explain the lack of eskers, or the ice may have been too thin in the areas of ice divide during final melting that a coherent drainage system could not exist (Shilts, 1985). In areas where eskers are prevalent, the main characteristics of esker distribution are the apparent Horton branching patterns, and the apparent concordance with topography (Flint, 1971). Aylsworth & Shilts (1989), however, have noted a lack of topographical control on esker paths in Keewatin. Over much of Canada, eskers tend to occur as an integrated Horton drainage pattern, with second order streams (Banerjee and McDonald, 1975) in most areas, and up to fourth order in the area of Keewatin (Shilts and Aylsworth, 1989). Horton classification (up to 3rd order in Labrador, Plate 1) for esker systems indicates that meltwater drainage which formed eskers was organized and functioned as an integrated system over large areas of the ice sheet. Eskers tend to slightly change their course to stay in a valley and usually on one side of it (Charlesworth, 1957, p. 421) unless the angle between the valley and regional ice flow direction is too large. When eskers cross high topography, they do so at the lowest pass, where an eroded channel is often found (Charlesworth, 1957, p. 421). In Sweden, large (and presumably long) eskers follow the topography more closely than small ones do (Lundqvist, 1983), and appear to be directly related in size to the size (width and depth) of the valley in which it is found (Hebrand and Åmark, 1989).

Eskers are likely the product of the reworking of glacial debris, and the amount of till and glacial debris in an area may be the controlling factor on the size and location of eskers. Around

Great Slave Lake in the Northwest Territories of Canada, in areas of high accumulations of till, eskers are abundant, while in areas of no or small accumulations of till, eskers are few (Charlesworth, 1957, p. 423). The amount of till is related to the type of bedrock, and in the area of Great Slave Lake, few eskers are located over resistant crystalline rocks of the Precambrian Shield, whereas they are abundant over more easily eroded Palaeozoic sedimentary rocks (Aylsworth and Shilts; 1989). In northern Saskatchewan, prominent eskers are located on Precambrian bedrock, where there is little else in terms of glacial deposits, which may indicate an almost complete remobilisation of glacial debris, as well as on the Athabasca sandstone, where there is a thick till cover (Schreiner, 1980). In south central Maine, the Great Pond esker (also called the Katahdin esker system) changes from a single ridge feature over crystalline bedrock to a braided system of ridges and valleys over sedimentary bedrock (van Beever, 1971). The topographic setting of the braided segment, likely the multiple ridge esker segment of Shreve (1985), is in a gently ascending reach of the esker.

In Keewatin, there are esker systems up to 700 km long, with unbroken segments up to 75 km long (Aylsworth and Shilts, 1989). Individual ridges are approximately 12-15 km apart (Banerjee and McDonald, 1975; St. Onge, 1984a and 1984b) in the area covered by the Laurentide Ice Sheet, and up to 20-50 km apart (Kaitanen and Stroem, 1978) in Scandinavia. Major eskers may have tributary and distributary ridges, analogous to fluvial systems (Charlesworth, 1957, p. 421). «Distributary» ridges are close to the main esker, and usually reconnect with it down-esker from the point of distribution. Esker systems form a sub-parallel dendritic pattern (Craig, 1960) on a regional scale that may reflect the shape of ice lobes and the irregularities of ice retreat, as in Finland (Donner, 1965). Near the trunk esker, tributaries bend at a sharp angle towards the trunk esker a few kilometres up-esker from the junction, which has been proposed to be due to the effect of the Coriolis force on esker drainage patterns (Aylsworth and Shilts, 1989).

Eskers tend to occur in areas of low relief (Hellaakoski, 1931; Flint, 1971, p. 214; Koteff & Pessl, 1981; Koteff, 1974; Hebrand and Åmark, 1989) or low angle slopes (Price, 1973, p. 140). Although eskers tend to be roughly parallel to late ice flow directions (Crosby, 1902; Hellaakoski,

1931; Bird, 1967; Flint, 1971, p. 214; Embleton and King, 1975; p. 473) and may even be used as ice flow indicators (Bouchard and Martineau, 1984), some eskers trend across, and can be perpendicular to, ice flow (Donner, 1965; Shilts, 1985; Lauriol and Gray, 1987). The implication is that eskers not parallel to ice flow indicate that the fluvioglacial systems have been emplaced in stagnant ice (Lauriol and Gray, 1987), or at least sluggish ice (Shilts, 1985). Banerjee and McDonald (1975) argue that there is no need for invoking a stagnating ice sheet for the formation of eskers, and argue that esker fans/deltas indicate well defined ice fronts, as do the close association of eskers with recessional moraines (Henderson, 1959). Howarth (1971) noted that the margin of Breidamerkurjökull in Iceland was active during the time of his study of eskers in front of that glacier. In most areas of Labrador, eskers are sub-parallel to ice flow indicators such as streamlined landforms and striae, which may indicate some activity in the ice sheet during esker formation (Vincent, 1989).

Morphology

Eskers vary from sinuous, narrow and steep-sided ridges with or without beads, aprons or pads, to multiple-crested, or even braided deposits (Meier, 1951; Flint, 1971; p. 215; Aylsworth and Shilts, 1989; Fig. 10). Sharp-crested eskers are usually found associated with present-day descending topography, while broad-crested eskers are found commonly in steeply ascending topography (Shreve, 1985). Typical eskers tend to maintain their width-height ratios down-esker, although the ratios may be different between esker systems (Ringrose, 1982). Some eskers increase in size downstream (Embleton and King, 1975, p. 467), which has been taken as an indication that eskers are formed simultaneously along their whole length, up to 150 km (Shreve, 1985). Individual ridges may be up to 80 to 90 m in height (Donner, 1965; Lee, 1965) with triangular cross-section (Charlesworth, 1957, p. 420). The morphology of eskers may be related to the conduit shape (Price, 1973) which, in Manitoba can be directly related to differing hydrodynamic conditions under different ice regimes. Short, wide and low eskers are associated with a cold-based, polar ice sheet, while long, narrow and high eskers are related to a wet-based, temperate ice sheet (Ringrose, 1982).

Along esker ridges, accumulations of fluvioglacial sediments can form hummocks, irregularly



Figure 10. Esker morphology. Oblique air photo of the most common esker morphology, the steep sided, sharp crested ridge (A), with flanking aprons (B). This is approximately km 45 of Lac Brisson esker.

undulating forms (Hebrand and Åmark; 1989) and planar forms such as plateaus and terraces (Aylsworth and Shilts, 1989; Hebrand and Åmark; 1989), on which meltwater channels and kettle lakes are found. The surface gradient of the planar forms is controlled by a threshold, which presumably controlled fluvioglacial drainage, such as a previously deposited glacial landform or a bedrock obstruction (Hebrand and Åmark; 1989). Between the esker ridge and other deposits of fluvioglacial sediments, there may be marginal troughs or even kettle lakes (Charlesworth, 1957; Banerjee and McDonald, 1975), which indicates the presence of sustaining ice walls, or ice blocks buried during the deposition of other types of fluvioglacial deposits associated with eskers. The emplacement of most fluvioglacial deposits associated with eskers likely postdates the deposition of the esker ridge itself, as is demonstrated by a flat-topped esker ridge emerging from a sandur in front of Breidamerkurjökull in Iceland (Howarth, 1971).

Esker crests may be sharp or flat-topped (Bird, 1967; Banerjee and McDonald, 1975). In flat-topped deposits, the sediment at the surface is often finer sand (Crosby, 1902). Flat-topped deposits have a horizontal crest after isostatic rebound, even if the ground surface is not level, which seems to indicate a stream course between ice walls (Lundqvist, 1983) or presence of a lake (Price, 1966). The tunnel cross-section may dictate whether the deposit will be flat-topped or sharp-crested (Price, 1973, p. 141). Experimental formation of an esker showed that eskers deposited in a «proglacial lake» retained their form if the water level was lowered slowly, but a flat-topped deposit resulted from disturbances during lowering of the water level (Hanson, 1943). The final shape of an esker is thus due to the deposition mode combined with post-depositional modifications, such as slumping, solifluction, frost action, eolian activity, wave action and beach processes in areas of submergence (Donner, 1965; McDonald, 1969; Granö, 1981).

A rather unique approach to the description of fluvioglacial landforms was taken by Stoelting (1978) in his study of eskers in eastern Wisconsin. Using a strictly geographical approach, he described eskers (sinuous forms, aligned parallel to meltwater drainage), type esker forms (similar to eskers, but field relationships left doubts as to their origin), crevasse forms (straight to sinous,

delimited by kettle holes), and morainic forms (straight and wide features, with a high relief). Stoelting's (1978) descriptive approach to esker studies puts esker segments along a continuous ridge into separate categories, which can only add to, and not resolve, the «confusion» he thought existed on the concept of an esker. His study is a contribution to the understanding of the morphology of eskers, but cannot add to a study concerned with the origin of eskers.

Stratigraphy

Eskers contain a wide range of sedimentary structures, which may or may not be laterally, or longitudinally continuous for more than a few hundred metres, because they form under variable flow conditions. Sedimentary structures in eskers range from massive to faintly cross-bedded units, indicating progradation of bar fronts (Banerjee and McDonald, 1975). There may be a poorly sorted matrix present in clast-supported units, indicating deposition as a slurry. Units of sorted fine sand, silt and clay, as well as pebbly mud may also be present. Sediment coarser than sand is typically water-worn (Flint, 1971, p. 215) and commonly shows anticlinal structures in cross-section (Crosby, 1902; Flint, 1971, p. 216) with an outward dip of 10° to 20° (Embleton and King, 1975, p. 468). Anticlinal structures may be due to secondary water currents of helicoidal shape up the esker flanks and down the tunnel ice walls (Shreve, 1972) or to removal of ice walls inducing collapse of the esker flanks and anticlinal-looking layering of the sediment (Charlesworth, 1957, p. 421; Cheel, 1982). Other structures, mostly associated with sand units, include ripples, dunes and graded bedding (Drewry, 1986, p. 152) as well as cut and fill structures (van Beever, 1971).

Because antidunes do not form in full pipe flow (McDonald and Vincent, 1972), the presence of antidunes in eskers has been attributed to flow in open channels, either in a partly filled tunnel, or subaerially, indicating deposition near the ice margin where tunnels are enlarged, or deposition during low flow events in late summer and fall. A structure which may be characteristic of tunnel flow is the sliding bed (Saunderson, 1977), which consists of clasts and matrix moving *en bloc* on the floor of the tunnel, not as a suspension, but as a bed. Gravel beds may have been transported as gravel bars during flood and deposited as sheets during low flow (Ringrose, 1982). Post depositional

structures are normal faults, indicating melting of supporting ice walls, and high angle reverse faults, implying melting of buried ice (McDonald & Shilts, 1975). Ball and pillow structures imply rapid dewatering (Cheel, 1982)

Interpretation of the environment of esker deposition was attempted by Ringrose (1982) by statistical analysis of stratigraphic data. She looked at the vertical and lateral continuity of sedimentary facies and found that two principal stratigraphic sequences, in conjunction with morphological characteristics, could be linked to environment of deposition and ice regimes. In the first sequence, the abundance of coarse gravel facies, either of the sliding bed or in-channel types were indicative of sedimentation in an ice tunnel in a rapidly melting, somewhat active ice sheet, in which local ice movements compensated for frictional erosion of the tunnel. An alternation between tunnel flow and open channel flow led to the alternation of the two types of gravel deposits. The second sequence was indicative of braided stream deposits, and the width of the deposit suggested deposition in a wide reentrant of the ice front, the ice unable to compensate for frictional enlargement.

Sedimentary structures are commonly interpreted in the context of three models: 1) the esker was deposited as a delta in a proglacial body of water - this includes subaqueous outwash deposits of Cheel (1982) and Henderson (1988), and beads of Shilts and McDonald (1975) - ; 2) the esker was deposited in a subglacial tunnel; or 3) the esker was deposited in a subaerial channel. Although each of these settings has a set of characteristic sedimentary structures - such as a distally fining sequence in the case of the deltas, anticlinal layering for tunnel deposits, and overbank flood deposits for the subaerial esker - it remains constant in all descriptions that the esker itself is a deposit of coarse sand and gravel, with cobbles and boulders up to 1 to 1.5 m in size, while any other fluvioglacial deposit is finer-grained (Fig. 11).

Lithologic composition

Only a few detailed studies of esker lithologies have been attempted (Hellaakoski, 1931; Trefethen and Trefethen, 1944; Lee, 1965; 1968; van Beever, 1971; Perttunen 1989). Other studies not directly focused on the lithologic composition of eskers (eg. Kaitanen and Stroem, 1978; Baker,

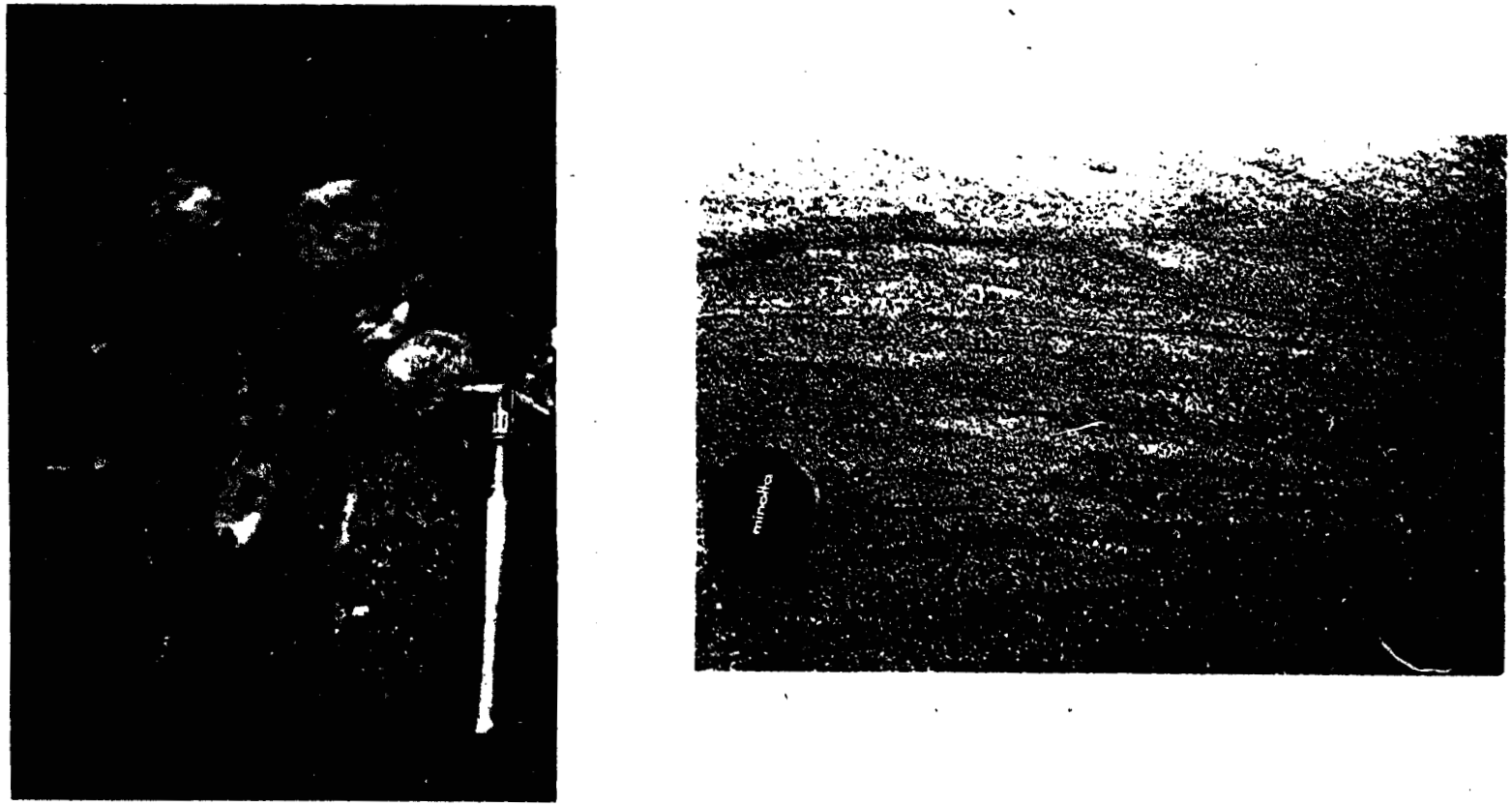


Figure 11. Esker and associated deposits material. Debris in an esker ridge is normally coarse-grained (A) while associated deposits are usually much finer grained (B).

1982), include some observations on the lithologies found in eskers.

Hellaakoski's study (1931) set out to answer two main questions: 1) how does esker composition change distally from the up-esker and the down-esker contacts of a particular rock type and 2) what is the relationship between esker lithologies and till composition. To answer the two questions, Hellaakoski (1931) studied the Laitila esker in Finland, which runs partly over rapakivi granite, a distinctive rock type. In till, rapakivi granite makes up to 55% of clasts 1.5 km down-ice from the proximal contact with its outcrop area (Fig. 12). Rapakivi granite outcrop area is not very wide, however, and even close to its distal contact, far-travelled clasts can be more abundant than rapakivi granites. Outside rapakivi granite outcrop area, rapakivi granite clasts in till are still present, but in smaller quantities (5-15%), while Archean rocks dominate all lithologies. Both rapakivi granites and Archean rocks appear similarly resistant to abrasion in till, while a sandstone located up-ice from rapakivi granite appears more resistant, as it (the sandstone) is found in larger quantities than rapakivi granite down-ice of rapakivi granite outcrop area. In the esker, the first appearance of rapakivi granite occurs 5-8 km from the up-esker contact. A marked decrease in rapakivi granite clasts occurs 5-8 km down-ice from the down-esker contact. The larger rapakivi clasts make up a more important proportion of their category than do smaller clasts in the first 10 km of the esker, while beyond, the opposite is true, indicating that the smaller clasts have been enriched by the breakage of the larger clasts. Clasts of more distant derivation than the rapakivi granites are found in low percentages, <7.5%.

Four main differences between the rapakivi granite percentages for till adjacent to the esker and the esker sediments are noted by Hellaakoski (1931). Firstly, the distance between the first appearance of rapakivi granite clasts in till and in esker sediments is about 4 km (lag distance). Secondly, stronger variations in the percentages of rapakivi granite in till indicate a poorly mixed material, while the slightly more even curve for esker debris indicates a better mix than till. Thirdly, the percentages of rapakivi granite rocks in the esker attain a higher value (~85%) in the esker than anywhere in the till, and appears to stay high for a greater distance from the source in the esker than

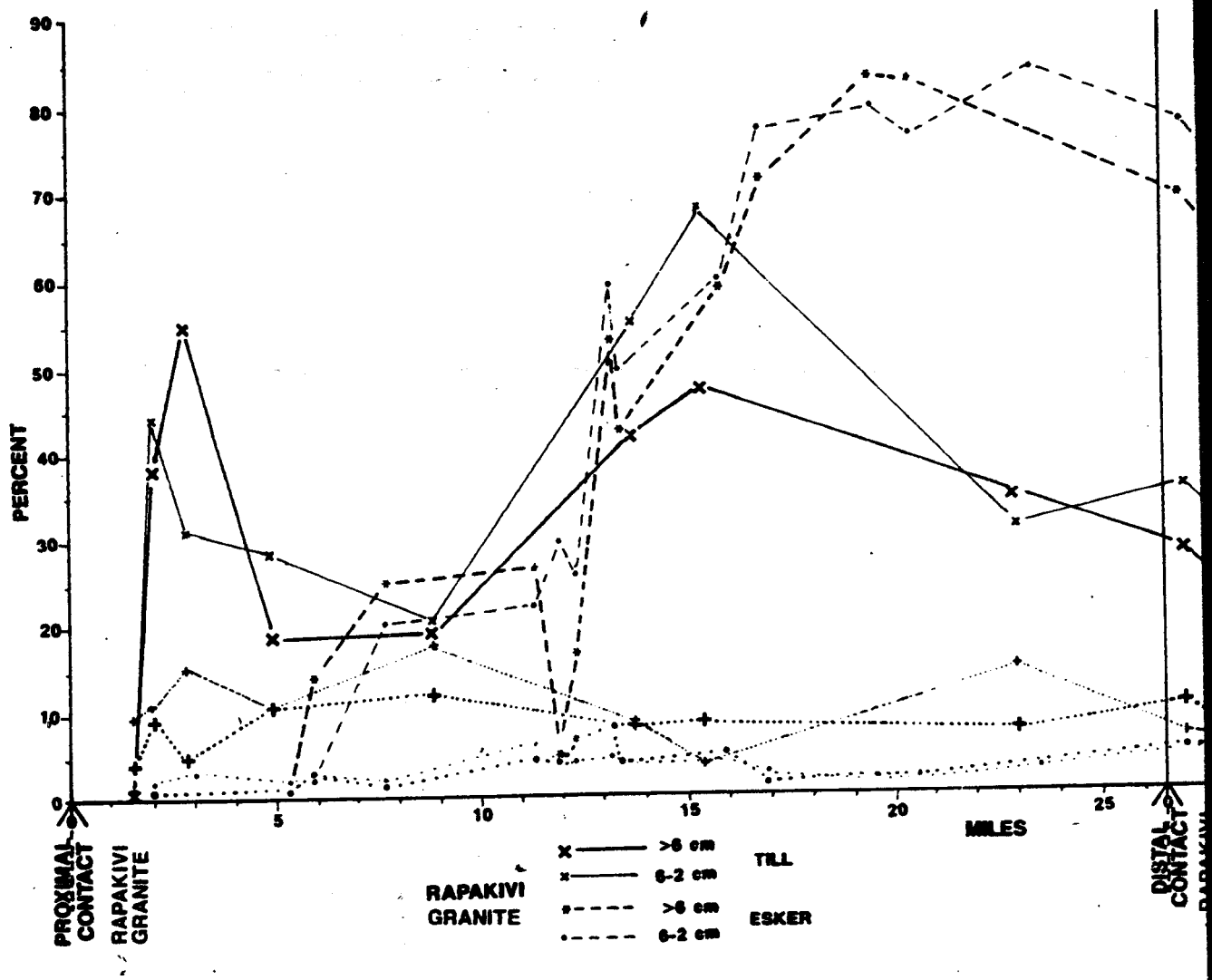
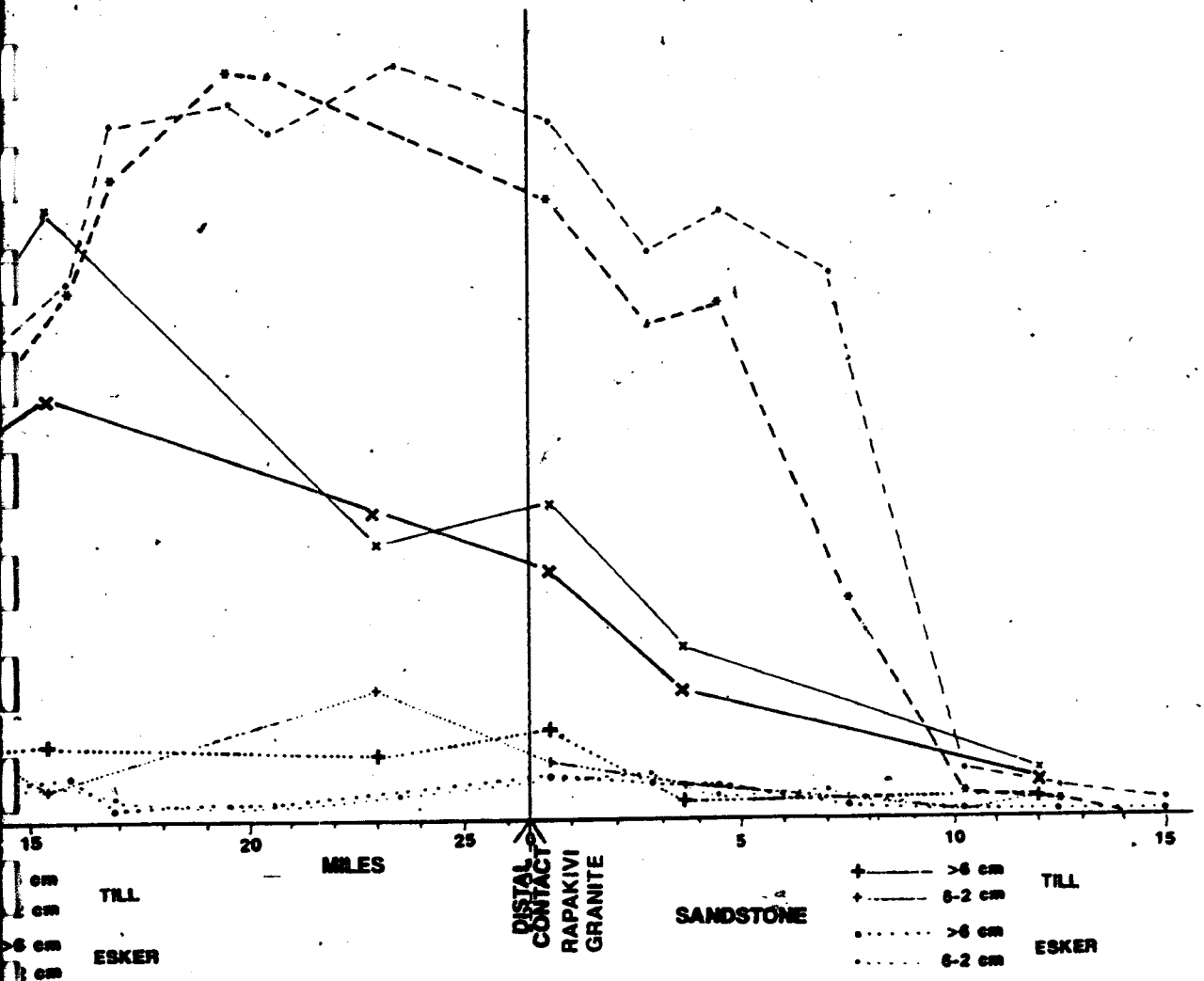


Figure 12. Clast lithologies in Laitila esker and adjacent till.



adjacent till.

Redrafted from Hellaakoski, 1931

in the till. Sandstone percentages are consistently higher in till than in esker material, for all size fractions, indicating that that bedrock type has an important influence on the sizes of clasts found in the esker with respect to those found in the till. Finally, during glacial transport, crushing and crumbling appear to be the most important size reduction factor, while in the esker, grinding and rubbing depend on the location with respect to the whole esker (core versus sides). The main similarity between lithologic curves for till and esker is the same rise and fall in percentages. The lithologic curves (rapakivi granite and sandstone) for the esker are displaced 4 km down-esker with respect to the corresponding till curve. Based on these observations, till is the parent material for esker gravels. The direction of the displacement from till to esker debris is the direction of flow of the meltwater stream which formed the esker. Eskers form subglacially, and derive their sediment from glacial debris transported at the base of the ice. As a result of this study, Hellaakoski (1931) added to the definition of eskers that they are petrographically similar to adjacent till.

Trefethen and Trefethen's study (1944) of the Kennebec esker in central Maine indicated that studies on the fine fractions did not yield much useful information, while larger fractions gave information on clast dispersal. The main findings of the study were that, in the esker and for both size classes, far-travelled clasts (>80 km) account for no more than 5% of all clasts, while the average travel distance is 5-13 km from bedrock sources. Fragmentation of the larger sizes tends to increase the proportions of a rock type in the sand fraction. The larger fractions also tend to be deposited sooner than the fine fraction, interpreted to be due to variations in the stream competency. The finer sizes have therefore a wider distribution than do the larger sizes. Clasts coming from granite mountains not crossed by the esker were found in it. Based on the absence of striae indicating ice movement towards the esker, Trefethen and Trefethen (1944) attributed the presence of those clasts to the input of debris by small englacial tributaries that did not form eskers, rather than to local ice creep towards the main esker tunnel. They did not study clast composition in till, but the esker is located on a till dispersal train from the granite mountains produced by regional ice flow to the SSE (Thompson & Borns, 1985). If granite clasts are found in adjacent till, then their presence in the

esker is to be expected, and thus 80 km of transport is not entirely glaciofluvial.

Lee (1965) studied the Munro esker which passes near Kirkland Lake in Ontario to assess the potential of using the lithologic composition of eskers as a tool for mineral exploration. Relations between transport distance and composition of different size fractions were investigated. Lee (1965) confirmed Hellaakoski's (1931) findings that the peak abundance of a rock type in esker sediments occurs some distance from the proximal contact with that rock type, although no relations with till (which was not examined) abundances are demonstrated. He named the distance between proximal contact of a rock type and peak abundance of that rock type in the esker, the transport distance «K». Values of «K» are similar for debris having similar hydrologic characteristics (size, specific gravity, shape). For dunite and magnetic rock fragments 3.35-8 mm, «K» is 13 ± 3 km while for larger dunites, it is less. For trachyte clasts 8-16 mm, «K» is 5 ± 3 km, while for gold grains, it is 3 ± 3 km. It was not possible to assess «K» for pyrope grains, but the parent source of pyrope in bedrock, based on data for other indicators, is believed to be within a 16 km radius of the first peak in the pyrope curve.

The esker studied by van Beever (1971) is located in south central Maine. He calls it the «Great Pond esker», although it has been referred to as the «Katahdin esker system» by Stone (1899) and Shreve (1985). Van Beever (1971) looked at the lithologies of clasts taken from within 1 m deep of the crest of the Great Pond esker and of till samples located close to the esker. The indicator lithologies used by van Beever (1971) are a redbed unit, a conglomerate, and a syenite. In till, for all size classes, the distance between proximal contact and peak abundance is, for the redbed unit, 1.4 km and for syenite, 1 km while for the conglomerate it cannot be determined, owing to the very low (<2%) percentages of conglomerate clasts everywhere. There was not a gradual increase in percentage in the till of any of the indicators to a maximum value, but rather an abrupt appearance of the indicator at maximum abundance within 1.6 km of the proximal contact. In esker sediments, the «K» value for redbed clasts is 3.8-5.5 km, while for syenite and for conglomerate clasts, «K» cannot be evaluated, due to the low (<3%) frequency of both indicators. For van Beever (1971), the

lithological composition of an esker depends on four factors: 1) the surface area of the bedrock source; 2) the resistance of the bedrock source to stream erosion; 3) the downstream distance from a bedrock source; and 4) the size of the fragments. In his conclusions, van Beever (1971) implies that the debris found in the esker was directly eroded from the bedrock by the meltwater stream, rather than erosion of the debris in the ice and of previously deposited till. He also concludes that the Great Pond esker is a subglacial tunnel deposit, and that the rapid decrease (5.5 km from the proximal contact) in the percentages of redbed clasts is the result of a short lived and overloaded stream, or of rapidly broken large clasts into smaller ones.

In southeastern Finland traverses along nine eskers were made in order to assess the distances of transport of garnets in fluvioglacial systems (Perttunen, 1989). Garnetiferous rocks occur north of the rapakivi granite area of southeastern Finland which itself is garnet-free. Samples were collected from the core of eskers where gravel pits existed, and from the base of 1 m deep pits dug at the esker crest. Non-garnetiferous pebbles appear in eskers 8 km down-ice from the contact between garnetiferous bedrock (up-ice) and the rapakivi granite area (down-ice). Garnets are present along the whole length of esker studied (79.5 km), in low (<5%) percentages over rapakivi granite, and in somewhat higher (5-15%) percentages over garnetiferous bedrock. Perttunen's model (1989) of garnet transport includes three levels of abundance. The first level is high abundance (11-40%), for a distance of 8 km from the source area. The second is intermediate abundances (3-11%), for a distance of transport of 8-37 km. The third is low abundances (<3%), for a distance of transport of 37-79.5 km. She cautions that low abundances (<3%) can be found in any of the three zones, and individually cannot be taken as an indicator of the sample being located far from its source. Rather, the pattern displayed by a number of samples may be more indicative of the source area of the mineral under study.

Studies on the lithologies found in eskers all show that there is a varying transport (3-13 km) down-esker between source of a lithology in bedrock and its peak abundance in esker sediments (Fig. 13). Factors influencing transport distances are rock type, size of outcrop area, and clast size under

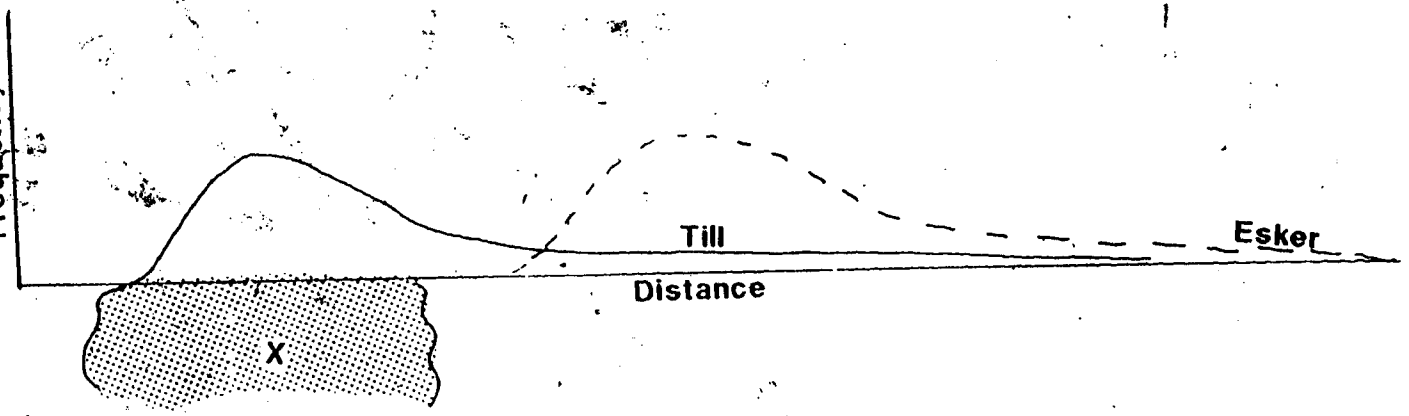


Figure 13. Hypothetical curves illustrating relationships between bedrock, till and esker composition. Component «X» is incorporated in till immediately down-ice from the proximal contact, with peak abundance some distance from it. In an esker, component «X» is also found down-ice from the proximal bedrock contact, but concentrations in esker are displaced down-esker from equivalent proportions in till.

study. Most studies suggest that the debris found in eskers is eroded from till and basal ice, except for van Beever (1971) who believes that direct fluvial erosion of bedrock by an esker stream is the main contributor to esker debris. Comminution of large clasts, enriching the smaller size fractions is recognized as an important factor in the dispersal of finer debris farther from the source. Size reduction mechanisms (smaller clasts are derived from bigger clasts) are thus an important part of the system and contribute to lengthen transport distances.

Origin of eskers

The history of esker studies has been reviewed by Jopling (1975). The first account of an esker-like feature in the British literature dates from 1699 when an Irish observer described a steep-sided, sinuous ridge, flat and wide enough at the top to use as a road (*in* Davis, 1979). The observer attributed the formation of the ridge to «some violent motions of waters» from the Noachian Deluge. Stratified drift (including eskers) was recognized during the latter nineteenth century to be of fluvioglacial origin, based on the presence of stratifications (indicating flowing waters) and on its close association with glacial drift. Thus, models of esker formation are closely interwoven with the evolution of the glacial theory. Observations which led to the development of two theories (supraglacial and subglacial) for the formation of eskers are: the occurrence of supraglacial meltwater and the presence of subglacial debris; the extensiveness of some esker systems; the general agreement of esker path with topography except where they cross transverse hills.

Supraglacial eskers

Supraglacial eskers were suggested because of the availability of meltwater on the surface of alpine glaciers. The debris necessary to form the esker can be englacial initially, but as the ice melts, the debris is uncovered and becomes supraglacial, and is then picked up by a stream (Charlesworth, 1957, p. 426). Alternatively, it was suggested that a supraglacial stream, at first, might melt by friction the underlying ice, until a base level is reached. From then on, it was assumed that the warmer (4°C), denser surface water would sink below the colder, lighter water, melting more ice. According to this theory, the colder water is constantly warmed at the surface, subsequently sinks, thus leading to a

continuous overturn (Crosby, 1902). The water percolates through the englacial sediment, melting more ice below. Deposition occurs when flow ceases in the stream channel (Crosby, 1902). Such a temperature separation, however, is unlikely to develop in turbulent supraglacial streams, such as exist on modern glaciers, and must have existed on the surface of the Laurentide Ice Sheet.

Shilts (1984) and Aylsworth and Shilts (1989) have suggested that the drainage pattern of supraglacial meltwaters may contribute to the integrated pattern of esker systems. According to this theory, eskers might be deposited in short segments near the glacier margin, downstream from where supraglacial meltwaters plunges down to the base of the ice via moulins. Headward migration of the moulins by frictional melting, roughly along the path of the supraglacial streams, places the surface drainage pattern at the base of the ice. That interpretation is based on the assumption that a dendritic drainage pattern is characteristic of a level, featureless plain such as the surface of a large ice sheet.

Conditions at the surface of an ice sheet differ from those of normal drainage. The ice sheet surface is characterized by a steeper slope down-glacier, less precipitation in the «catchment» area of the streams, and the dynamic nature of flowing ice, the network of drainage routes differ somewhat from river patterns. Supraglacial meltwater streams tend to form a sub-parallel, dendritic network, with a decrease in stream density up-stream, and large integrated patterns are rare over actively flowing ice (Sugden and John, 1976, p. 285). The presence of moulins and crevasses may substantially alter the surface drainage pattern on an ice sheet by redirecting meltwaters to the base of the ice, and weaknesses in the ice may be exploited by meltwaters to form straight channels (Sugden and John, 1976, p. 285).

A final argument against supraglacial eskers in a continental setting is that much of the surface of a continental glacier is practically free of sediments (Embleton and King, 1975, p. 473; Pessl and Frederick, 1981), the only available surface debris coming from nunataks. This scattered material could hardly be expected to contribute enough sediment to form the large and widespread esker systems found in continentally glaciated areas. Supraglacial debris can only contribute to an esker pile

if it reaches the base of the ice, likely through moulins.

Subglacial eskers

Subglacial eskers were proposed because deposition occurs subglacially (Stone, 1899). According to this theory, subglacial tunnels were thought to be full of water and sediment flowing at varying velocities, except at later stages where and when eskers were deposited in short (few kilometres) segments in tunnels (Charlesworth, 1957, p. 427). As the ice retreats, segments are added in an up-esker direction to those previously deposited. The time-transgressive deposition of esker segments would make the esker appear as a long, continuous ridge (Banerjee and McDonald, 1975; Hebrand and Åmark; 1989).

The subglacial theory was used to explain the fact that eskers have a tendency to follow valleys (Flint, 1971, p. 216) and that melting of underlying ice would destroy sedimentary structures in eskers due to collapse of the sediments (Flint, 1971; p. 218; Banerjee and McDonald, 1975; Coupland and Mayewski, 1980; Aylsworth and Shilts, 1989). Petrie and Price (1966), however, noted that an esker ridge maintained its form after over 25 m of lowering from ice wastage. Price (1973, p. 156) also observed that an esker at Breidamerkurjökull was lowered 10 m/yr without destruction of its form. Internal structures could not be observed in Price's study due to the coarseness of the sediment and collapse of section exposures (Price, 1973, p. 145).

While subglacial eskers should be buried by outwash (Crosby, 1902), eskers have been observed to emerge from a sandur as it was lowered from ablation of buried ice (Howarth, 1971). Crosby (1902) also believed that till could not be found on top of eskers, a «fact» he took as indicating that subglacial deposition was not possible. More recent observations by Embleton and King (1975; p. 473), Fleeger (1986), Mannerfelt (1981), Ringrose (1982) and Saunderson (1975), amongst others, have shown that till is sometimes found on top of eskers.

Eskers formed in subglacial tunnels debouching in a glacial lake or sea, can lead to formation of a subaquatic fan or delta (bead) with a narrow ridge of fluvioglacial sediments deposited in the tunnel leading to it (de Geer, 1897; Fig. 14). Annual retreat during the summer, with stillstand during

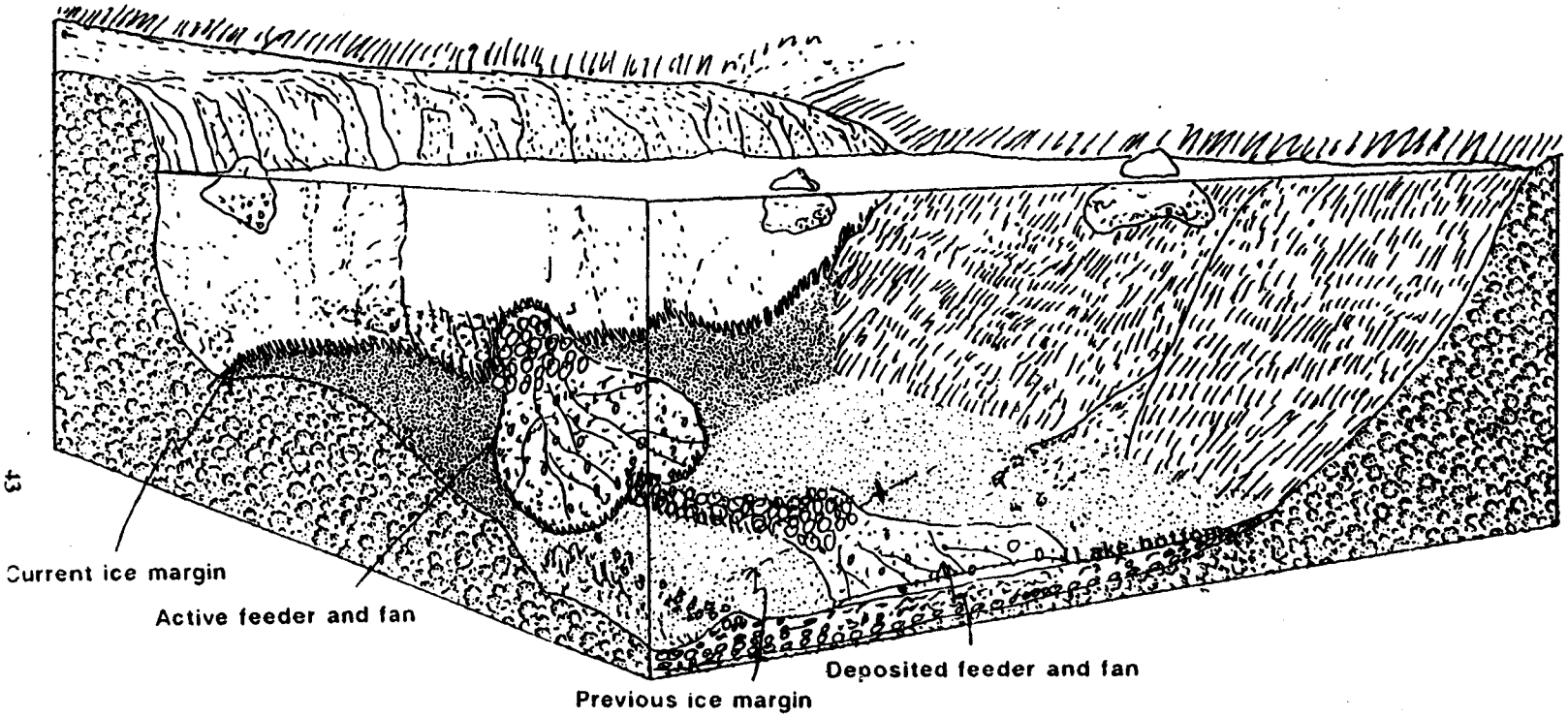


Figure 14. Formation of a beaded esker. The fan (bead) is deposited under wtaer, at the ice margin, while the feeder (esker) is deposited in a subglacial tunnel.

(Modified from Powell, 1981)

the winter, of the ice margin would lead to the building of successively younger beads in an upstream direction, and, time-transgressive deposition of a series of segments on an adverse slope could lead to a deposit that would appear to climb up-hill (Banerjee and McDonald, 1975). If the formation of fans and deltas is annual, then the average distance between them is the average annual glacial retreat. Continuous retreat could produce a quite long esker system, with somewhat regularly spaced fans or deltas. De Geer eskers have been described from numerous localities, wherever short esker segments leading to a fan or delta-like deposit are found (eg. Donner, 1965; Lundqvist, 1965; Banerjee, 1969; Banerjee and McDonald, 1975; Cheel, 1982; Henderson, 1988). Even though an annual nature for the beads is not always possible to demonstrate, their presence along the esker system requires that the ice margin terminate in a lake/sea, and be stable over a period of time for deposition of the bead to occur.

Modern theories on esker formation associated with the decay of continental glaciers agree on one point: the tunnels were subglacial (Shreve, 1985; Aylsworth and Shilts, 1989; Hebrand and Åmark, 1989). It is now recognized that ancient eskers had to be formed in the bottom meters of the ice sheet simply because that is where the debris was found (Pessl and Frederick, 1981; Shilts, 1984). Supraglacial meltwater may be involved in esker forming processes, but deposition occurs at the base of the glacier (Ringrose, 1982; Shilts, 1984; Shreve, 1985; Aylsworth and Shilts, 1989; Hebrand and Åmark, 1989). Considering the thickness of ice involved, the subglacial system may be defined as the bottom 30 m of the ice sheet, which would be about 1% of the total thickness. The length of tunnel in which esker deposition occurs varies from nothing (deposition occurs in front of the glacier (Hebrand and Åmark, 1989)) to a few kilometres (Shilts, 1984; Aylsworth and Shilts, 1989) to simultaneous deposition along an esker 150 km long (Shreve, 1985). In most esker studies, the debris forming the esker is simply assumed to be available, usually by erosion of previously deposited till, or of debris located inside the ice, rarely by direct fluvioglacial erosion of the bedrock.

METHODOLOGY

Field techniques

Aerial photographs covering central, western (approximate scale 1:33,500) and northern (approximate scale 1:63,000) Labrador were reviewed in preparation for field work. Esker systems were mapped at a scale of 1:250,000 and compiled regionally at a scale of 1:1,000,000 (Klassen *et al*, in prep.). Eskers as narrow as 50 m can be recognized on air photos, but the esker symbol on a 1:250,000 map covers a width of approximately 500 m, and on the compilation map, only the widest features can be represented to scale. While a line can be drawn along esker features, it is not representative of the size of the esker, but shows the occurrence and extent of esker systems. A more detailed study (1:50,000) of the eskers visited in the field was carried out. At that scale, the esker symbol covers a width of only approximately 100 m. It was therefore possible to map most features of esker systems, with the exception of the smallest aprons.

The eskers were identified on the air photos by their morphology, a narrow ridge, usually subparallel to late ice flow directions, as indicated by fluted landforms. Because a gravelly terrain is usually better drained than a silty terrain, and colonized by caribou moss and scattered spruce trees, eskers and other gravelly deposits usually appear with lighter tones on air photos covering forested areas. Sandier deposits have a uniform light to medium gray tone, while coarser deposits appear as spotted light and dark gray (Fig. 15). A thin blanket of gravel often covers other deposits (ribbed moraines, fluted landforms, ground moraine). Although its thickness cannot be assessed from the photographs, it is assumed to be thin (less than 2-3 m), as the blanket does not hide the morphology of the other deposits.

In densely vegetated areas, it is not always possible to locate the contact between fluvioglacial material and glacial material. It was not possible either, from air photos combined with topographic maps, which have a contour interval of 50 feet, to accurately assess the height of eskers and their associated deposits. Width estimates of the ridge itself, and of the whole fluvioglacial complex, however, could be made from air photos. Nevertheless, measurements of esker parameters were

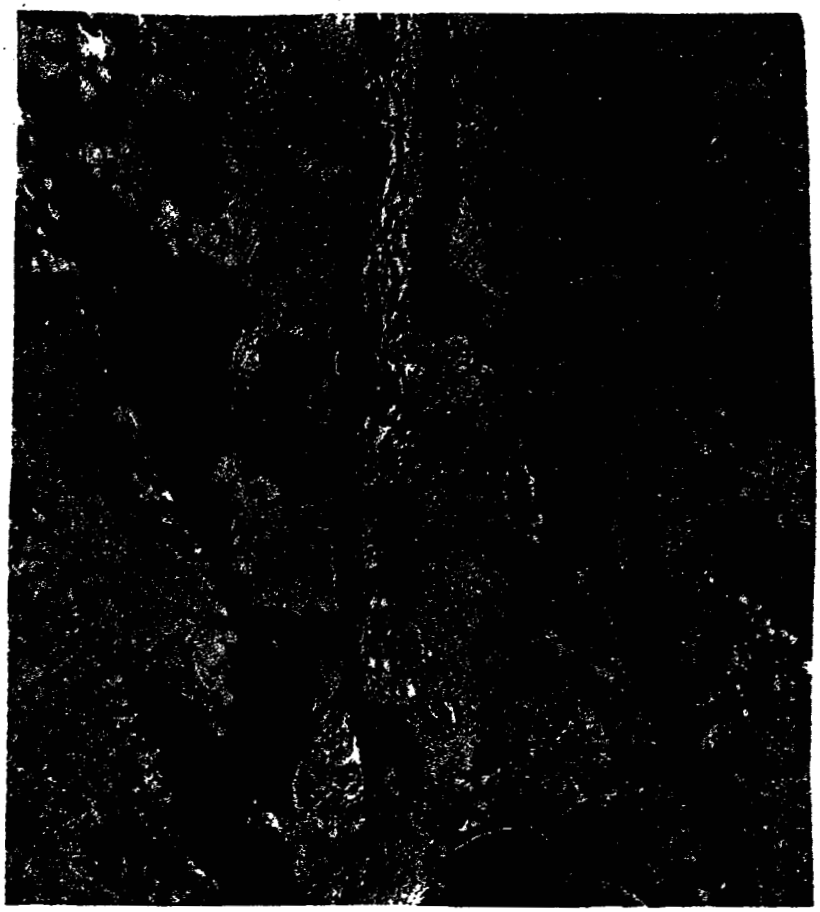


Figure 15. Fluvioglacial deposits on an air photo (NAPL A12017-12). Note the light colour of glaciofluvial deposits on the photo, in contrast with the dark grey which is characteristic of till. Esker ridges are represented by the symbol >>>>>>>, indicating the direction of meltwater flow. Associated deposits are: splay (Ks); pad (Kp); apron (Ka), thick blanket (Kb); blanket over ribbed moraines (Kb/Tr); and blanket over till (Kb/T). Kettle holes are found in the splays, on one of the pads (*) and dividing the double and multiple crested esker segments. An area of till (T) is located east of the glaciofluvial corridor.

attempted on combined air photos and topographic maps, and in the absence of other information, they provide some general constraints and information on esker parameters (Table 1).

A total of 305 esker samples and 295 till samples (about 2-3 kg of sediment, in which all stones of about 10 cm and larger were removed) were collected to assess compositional variations by lithologic and mineralogic analyses (Table 2 for sample distribution; Appendix III for sample location). Of the till samples, 28 in central Labrador were collected in 1983 (Bolduc, 1985) and 131 in northern Labrador were collected by Martin Batterson (Geological Survey of Newfoundland) in 1983 and 1984. While in the field, a portion of the esker samples was wet sieved to separate the 4-5.6 mm pebble fraction used for lithologic counts. Samples from northern Labrador were further separated (0.71 - 0.79 mm) for mineralogic analysis.

Samples were collected at depth of 50 to 100 cm, and at an interval of approximately 1 km along the crest of selected trunk eskers, and 5 km on tributary eskers At the junction between tributary and trunk eskers, samples were collected at a closer interval (about 0.5 km) upstream and downstream from the junction. In addition, in some areas, multiple samples were taken where stratigraphic sections were exposed, at a vertical spacing of approximately 1 m, and, if possible within different stratigraphic units. Associated deposits were sampled in some locations. Till samples were collected adjacent to eskers at irregular intervals of 5 to 10 km, and as part of a regional scale sampling program by the Geological Survey of Canada (Klassen & Thompson, 1990).

At each sample site, the esker was characterized according to the distribution and size of surface boulders, morphology of the ridge, and occurrence of associated landforms. Where exposures permitted, lithologic counts on the cobble fraction were performed on clasts of 5-20 cm. At least 100 cobbles were picked at random from the base of exposed sections or from the surface of non-vegetated esker crests and piled up on a tarp, then separated into lithologic categories. Those clasts which could not be readily identified were split open to expose a fresh surface. Clasts which could still not be identified, were put into an «unclassified» category. The number of clasts in each category was then recorded and transformed to percents. A number of replicate counts were executed on different days

ESKER	LOC'N C,W,N	LENGTH km	LENGTH STUDIED km	BASIN SIZE km²	TRIB	SI	TREND °	GRADIENT	HEIGHT OF ESKER M,m,a m	WIDTH OF ESKER M,m,a m	WIDTH OF ESKER COMPLEX M,m,a m
GABBRO	C	90.00	90.00	4424	3	1.05	106	-0.0005	17,4,10	300,50,100	800,400,600
OSAK	C	230.00	155.75	17220	10	1.10	136	-0.0022	16,4,12	300,30,100	1100,100,500
1		81.00				1.07	147	-0.0013			
2		66.50				1.02	115	-0.0005			
3		82.50				1.09	148	-0.0444			
SHABO*	W	310.00	116.00	11916	11	1.07	154	0.0001	30,3,15	350,30,100	1200,100,600
SHABO		116.00				1.08	168	-0.0010			
1		5.75				1.11	138	-0.0014			
2		85.75				1.05	175	-0.0013			
3		25.50				1.32	185	0.0002			
DEMILLE		330.00	129.00			1.04	145	0.0003			
1		85.00	35.50			1.05	130	-0.0005			
2		93.50				1.04	158	-0.0007			
ASH	W	320.00	70.00	12732	10	1.10	145	-0.0001	16,3,12	300,40,100	1500,150,500
1		5.00				1.00	178	-0.0040			
2		44.50				1.05	148	-0.0013			
3		5.50				1.10	182	-0.0009			
4		15.00				1.05	170	-0.0060			
BRISSON	N	99.50	78.50	3896	1	1.10	068	-0.0025	20,4,12	250,30,150	1200,100,650
1		40.75	19.75			1.03	086	-0.0032			
2		53.75				1.08	057	-0.0015			
3		5.00				1.05	018	-0.0074			

Table 1: Characteristics of esker systems which were studied in Labrador. ESKER: name of the system; LOC'N: location; C;W;N: central, western or northern Labrador; LENGTH: overall length; LENGTH STUDIED: section of the system which was looked at; BASIN SIZE: area of the drainage basin of the whole system; TRIB: number of tributaries to the trunk; SI: sinuosity index; TREND: orientation; GRADIENT: gradient, corrected for differential isostatic rebound; HEIGHT OF ESKER: taken from the esker crest to the till plain, or the floor of gravel pits (M: maximum height; m: minimum height; a: average height); WIDTH OF ESKER: from air photos, measured across the ridge itself (M: maximum height; m: minimum height; a: average height); WIDTH OF ESKER COMPLEX: from air photos, includes aprons, pads and splays (not blanket) (M: maximum height; m: minimum height; a: average height).

Location	Cobble counts	Pebble counts	Sand counts
Central Labrador	9	62	
till	28	51	
Gabbro	8	26	
Ossokmanuan			
Western Labrador		72	
till		76	
Shabogamo		27	
De Mille		30	
Moose Head		20	
Ashuanipi			
Northern Labrador		110	
till	33	75	161
Lac Brisson			69

Table 2. Sample distribution according to analysis type. Only those samples taken for pebble and sand counts were taken back to the laboratory, while those for cobble counts, once the count was performed, were left in the field.

than the original count, and using a different group of cobbles, to assess counting variability.

Stratigraphic sections were exposed within burrow pits associated with construction activities and at stream cuts. Exposures are few, and they are commonly slump-covered with the base of the esker rarely exposed. A section about 1 m wide was cleared with a small folding shovel, from the top of the esker as far down as possible. Height of the esker crest above adjacent terrain was estimated with the use of an altimeter. Stratigraphic units were described qualitatively mainly according to the size fractions present in the deposit (boulders, cobbles, pebbles, sand, silt-clay), as well as to the amount and type of matrix (matrix-supported mixed units, for which a descriptor, coarse, medium, fine or very fine, indicates the size of the clasts, while the matrix comprises smaller sizes) (Table 3).

Because of the constraints imposed by the limited development of Labrador, most observations relate to the upper part of the esker ridge (stratigraphy, lithologic composition). As a result, the interpretation on lithologic composition made from the collected samples is biased towards compositional changes along the crest of the esker, while stratigraphic interpretation is made from the narrow exposures.

Laboratory techniques

Pebble subsamples (from wet-sieving esker samples in the field) were air dried and sieved to remove material smaller than 4 mm. Variable size subsamples were necessary because of the highly variable pebble content in esker sediments in order to separate at least 40-50 g of pebbles (4-5.6 mm) for lithologic categorization. The average weight of one pebble being about 0.1 g, the number of pebbles in 40-50 g of pebbles is 400-500, sufficiently to reduce counting variability to <3 wt%. Not all samples contained pebbles, and only those which did contain pebbles for central and western Labrador are reported in this work.

Clay and iron oxide coatings were removed by soaking the pebbles in a mild solution of sodium metaphosphate overnight, agitating the sample to loosen all particles adhering to pebbles while taking care not to break any of the pebbles, rinsing thoroughly and air drying. The washed sampled was then re-sieved through a 4 mm screen to remove all <4 mm particles detached during

Type	Description	Origin
Clast-supported		
Boulders	20-30 cm, up to 50-70 cm rounded to well rounded gravel, clast-supported Matrix is coarse sand to small pebbles	Armoured bed or bedload sheet Very high energy flows
Cobbles	10-15 cm, rounded to well rounded gravel, clast-supported Matrix is coarse sand to granule	Armoured bed or bedload sheet High energy flows
Pebbles	4-5 cm, up to 10 cm rounded to well rounded gravel, clast-supported Matrix is coarse sand to granules	Armoured bed High energy flows
Mixed units		
coarse mix	Boulders in a coarse sand to pebble matrix	Sliding bed of progressively lower intensity
medium mix	Cobbles in a coarse sand to pebble matrix	
fine mix	Pebbles in a coarse sand to granule matrix	
Very fine mix	<1 cm clasts in a sandy matrix	Bed load; moderate energy flows
Sand	Undifferentiated coarse, medium and fine-grained sand, Climbing ripples; planar laminations, normal and reverse faults	Bed load; low intensity flows
Silt-clay	Thin layers of silt and clay, sometimes as rhythmites	Suspended load
Diamicton	Till-like deposit, with 40-50 cm angular clasts in a silty matrix	Glacial deposit

Table 3. Description of sediment types found in fluvioglacial deposits in Labrador

the washing. Pebble subsamples weighing more than 100 g were split using the opposite quadrants method (Paré, 1982). In this splitting method, the pebbles are uniformly spread over a sheet of paper and divided into four groups by tracing a cross through the pebbles. The pebbles in two opposite quadrants are removed, and the lithologic count is performed on the remaining pebbles.

All prepared samples were separated into lithological categories by visual inspection, followed by an inspection of each group of pebbles under a binocular microscope to ascertain that all pebble were placed into the proper lithologic category. Each lithologic group was weighed on an electronic scale and the weights recorded. The weights were converted to weight percents. A number of replicate counts, on the same pebbles for unsplit samples, and on a resplitted portion of large subsamples, were executed on randomly selected samples on a different day than the original count, to assess counting variability while avoiding remembering the original count.

In northern Labrador, because of the unusual properties of feldspars from the Strange Lake peralkaline granite (Mariano, 1988), the subsamples were further separated to remove the sand fraction (0.71-0.79 mm). This size category represents sieves with screen openings of 0.75 ϕ and 0.5 ϕ respectively. Using sand of this size fraction allowed a rapid dry sieving without particular prior preparation, and no special preparation was necessary before the grains could be observed under cathodoluminescence (Mariano, 1988, pers. comm.). A piece of two-way tape was then placed on a glass slide, and sand grains were sprinkled on the tape with a metal spatula, which was wiped clean between samples. Two glass slides were introduced into the vacuum chamber of the cathodoluminoscope (Nuclide luminosocope ELM 2B), and a vacuum was pumped for approximately 5 minutes, until the pressure in the chamber reached approximately 30-40 millitors. An electron beam was then shone onto the sample, the settings of the power supply being as follows: power at 9 kilovolts, beam current at 0.6 milliamperes, low focus at 35, and the bleeder slightly on, allowing some air to penetrate the chamber. With the preceding settings, feldspars from the Strange Lake peralkaline granite luminesce red to orange, and other minerals which may or may not come from the Strange Lake peralkaline granite luminesce blue to white (quartz) and yellow (potassium feldspar).

The number of each type of luminescing minerals, as well as the total number of non-luminescing minerals, were recorded and transformed to percents. To assess counting variability, replicate counts were executed on different day than the original count, and using a new sprinkle of grains on a new slide.

Sand grains from samples used in the cathodoluminescence study, as well as mounts of rock samples from the Strange Lake peralkaline granite, were analyzed semi-quantitatively using a JEOL 733 Superprobe, available in the Department of Material Sciences of Lehigh University to confirm the presence of red-luminescing feldspars in the samples known to come from Strange Lake peralkaline granite. With this instrument, cathodoluminescence can be achieved, and an analysis of the elements composing the grain can be realised. The result of the analysis, performed by P.H. Benoit of the Department of Geological Sciences of Lehigh University, indicates that the red to orange luminescing minerals are low-anorthite plagioclase. It also indicated that the riebeckite and its brown altered core so characteristic of the Strange Lake peralkaline granite do not luminesce.

The clay fraction of till samples was removed for geochemical analyses by a commercial laboratory (Chemex Ltd of Vancouver, British Columbia) and used for the regional study of till geochemistry in Labrador by Klassen & Thompson (1990). The fraction of the sample from which the clay was removed was dry sieved to separate the 4-5.6 mm pebbles. The washed pebbles were prepared and characterized similarly to esker pebbles. The amount of pebbles in till is highly variable, and in most cases less than 50 g of pebbles were available. Caution should be used in interpreting results from till samples which have less than 10 g of pebbles, although they, along with all other till samples, have been used in constructing till dispersal trains. Not all till samples contained pebbles, and only those till samples from central and western Labrador having pebbles are reported here. Because some (131) samples in northern Labrador were collected by M.J. Batterson for a different purpose, most samples did not contain pebbles. All samples, however, contained a sufficient amount of sand grains for a mineralogic count described previously.

To test the validity of trends which were picked up during the analysis of the large body of

information gathered in the course of this study, a number of statistical techniques have been applied to the transformed data (percent cobbles; weight percent pebbles, percent sand grains). Regression analysis supplied by QUATTRO® from Borland, one-sample T-test and tests of normality provided by Statgraphics® from STSC were used. Cluster analysis supplied by a software package, SPSSX®, was also used, Statistics on stratigraphic sections, and tests used to discriminate between till and esker lithologic population, were calculated using QUATTRO®. The stratigraphy was treated using upwards transitions residual matrix analysis, following Selley (1969) and Ringrose (1982), and refined by Walker (1979, 1984) and Harper (1984).

RESULTS

ESKER DISTRIBUTION

Organization of esker systems on the Labrador Peninsula

In Labrador, the distribution of eskers can be described in terms of three distinct zones (Fig. 6; Plate 1). The first one is referred to as the «no esker zone» (zone A, Fig. 6) and is characterized by few to no eskers. It is located near coasts, along the Churchill River, over Harp Lake Massif, and in the central area («ice divide») of the peninsula. The second zone the «disorganized esker zone» (zone B, Fig. 6), is characterized by small esker segments (<20 km long), that define no obvious drainage organization. It fringes the «no esker zone» along the Gulf of St. Lawrence, to the east and south-east of the central «no esker zone» and surrounds the Harp Lake Massif. The third type of zone, the «organized esker zone» (zone C, Fig. 6), has long eskers (up to a few hundred kms) organized as a Horton-type sub-parallel drainage pattern, with main and tributary eskers defining elongate drainage basins (Plate 1), and is located near Ungava Bay, north of Hamilton Inlet, and over the area which roughly corresponds to the Lake and George plateaux.

The «no esker zone» along the coasts is not devoid of fluvioglacial sediments. Generally, small eskers on plateau areas lead to valleys in which extensive proglacial fluvioglacial sediments are located, but in which eskers have not developed. Over the Harp Lake Massif, the lack of eskers may be due either to the near absence of till, without which eskers evidently can not be built, or to the

lack of meltwater plumbing within the ice sheet in that location. Local relief near the Massif is in the order of 400 m, and presumably, meltwaters from the interior of the ice sheet flowed around the Massif rather than over it, as shown by esker segments at the base of the Massif which curve around it, rather than climb over it. The «no esker zone» located in the central area of the peninsula is also the site of the presumed late glacial ice divide (the lack of eskers in that area was part of the criteria used to locate the ice divide) and of glacial lake McLean (Dyke & Prest, 1987). Under glacial lake Naskaupi, there are numerous small esker segments leading into and out of the George River Valley. Near residual centres, the ice mass was likely too thin to maintain a coherent subglacial drainage network controlled by glaciostatic pressure gradients, as postulated for Keewatin by Shilts (1985).

The «disorganized esker zone» located east and south-east of the central «no esker zone» (Fig. 6, Plate 1) may be explained by the thinning of the ice sheet, at which time no coherent drainage system could be maintained (Shilts, 1985). The «disorganized esker zone» located along the southern «no esker zone» may be attributed to the rapid deglaciation near the Gulf of St. Lawrence, which may not have permitted building of long and integrated esker segments, as suggested by the isochrone reconstruction of King (1985). Near the Harp Lake Massif, the reason why a «disorganized esker zone» should exist is not clear, but may be related to the rearrangement of meltwater drainage due to the topographic obstacle represented by the Massif.

The «organized esker zone» represents that sector of the ice mass which maintained coherent integrated meltwater drainage at the base of the ice sheet allowing formation of integrated esker systems. In this zone, esker systems are up to 420 km long (when small gaps between esker segments are measured with esker segments) and the drainage basin area of an individual esker system is up to 17,200 km^2. There is a linear relation

$$L = 68 + 0.02A$$

between longest esker in a system and size of basin area ($R^2 = 0.81$; Fig. 16A), but the relation may also be due to how widely separated (average 12-15 km) sub-parallel long eskers are within a system.

An esker system (marked by an asterisk on Fig. 16A and 16B) located near Smallwood

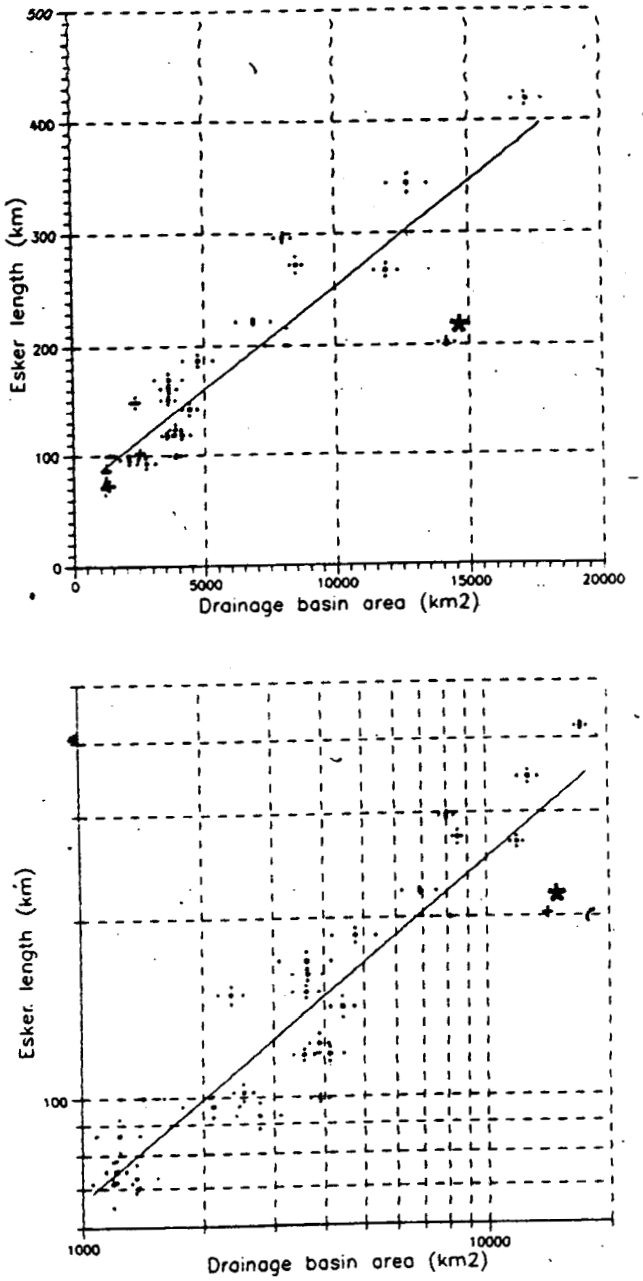


Figure 16. Relationship between drainage basin size and esker length. The 99% confidence interval is plotted for each basin area (measured with a planimeter) and each esker length (measured with an opisometer). Length of the longest esker is recorded, which may not be the «trunk» esker of the system. Asterisk (*) indicates the position of that esker system partly located in Smallwood reservoir, which has eskers at an angle (70°) to late ice flow direction. A: Linear function B: Power law function

Reservoir is at an angle of up to 70° to ice flow directions, and has a very different shape (square) than other systems (rectangular) in Labrador. Because of the particular conditions which led to the formation of this system (see p. XX), it may be excluded from the analysis. The correlation coefficient for the linear relation

$$L = 59 + 0.02A$$

is improved to $R^2 = 0.91$.

For fluvial systems, the relationship between mainstream length and basin area can be expressed by the following equation (Hack, 1957)

$$L = aA^b \quad (1)$$

where L is the mainstream length, A is the basin area, a and b are constants (the intercept and slope of the regression line on a log-log plot). The exponent b is greater than 0.5, implying that drainage basins tend to be more elongate as their size increases (Robert and Roy, 1990). This is an allometric (scale-related distortion of geometry) interpretation of the relationship. A fractal interpretation of the length to area ratio relates measures made on different scale maps, for each of which a and b are calculated. A combination of both interpretations explains the relationship (Robert and Roy, 1990). Nevertheless, b appears to always be less than 1, therefore an exponential relationship appears to be true for fluvial systems.

Applying a power law function for fluvioglacial systems in Labrador (Fig. 16B) as for fluvial systems, the relationship between esker length and drainage basin area is:

$$L = 1.64 * A^{0.58}$$

The correlation coefficient $R^2 = 0.84$ is a better fit to the data than the linear function when all esker systems are taken into account. If the anomalous esker system is removed from the analysis, then the equation becomes

$$L = 0.81 * A^{0.62}$$

but the correlation coefficient is only improved to $R^2 = 0.86$, less than for a linear relationship. A linear relationship between longest esker length and drainage basin area is valid for fluvioglacial

systems, indicating that drainage basins do not become more elongate as their size increases, and that the width of the fluvioglacial corridor stays constant.

There appears to be a fundamental difference between fluvial and fluvioglacial systems, which is that fluvioglacial drainage basins retain their elongate shape regardless of esker size. While supraglacial meltwater systems resemble fluvial systems (dendritic drainage pattern) over a level featureless plain (Aylsworth and Shilts, 1989), subglacial drainage must be controlled by other factors, such as underlying topography and amount of water to evacuate. Subglacial topography varies over Labrador, and it is more likely that the length-area ratio is related to the amount of meltwater to evacuate. The regular spacing between eskers (12-15 km) also reflects the amount of meltwater to drain, and is therefore a characteristic of the subglacial drainage of an ice sheet. The length-area ratio and the regular spacing between eskers indicate that of the quantity of meltwater present subglacially is efficiently evacuated by an elongate tunnel system represented today by esker traces.

In general, the overall orientation of eskers in the «organized esker zone» is sub-parallel to late ice flow directions, as recorded by streamlined glacial landforms (area A, Fig. 17). To the east, eskers are oriented NE to E, while to the south, their orientation changes from SE to SW, radiating about the location of the presumed ice divide. The prevalent pattern of esker distribution in the «organized esker zone», indicates that the main control on esker location is by the glaciostatic gradient imposed on the subglacial drainage system by the ice mass. Thus, eskers are generally oriented parallel to late ice flow. There appears to be a control from subglacial topography on the details of the paths, such as detours around hills, and crossing high topography at low passes.

Near Smallwood Reservoir there is a difference of up to 70° between esker orientation and ice flow trends (area B, Fig. 17). This area may mark a major reorganization of glacial flow at a time where local influences on glacial dynamics during the time of esker formation, played a more important role than overall glacial conditions during the formation of drumlins and other fluted landforms. The most probable local control may have been a presumed ice stream located over Churchill River valley and Hamilton Inlet (Klassen and Thompson, 1987), which could have drawn

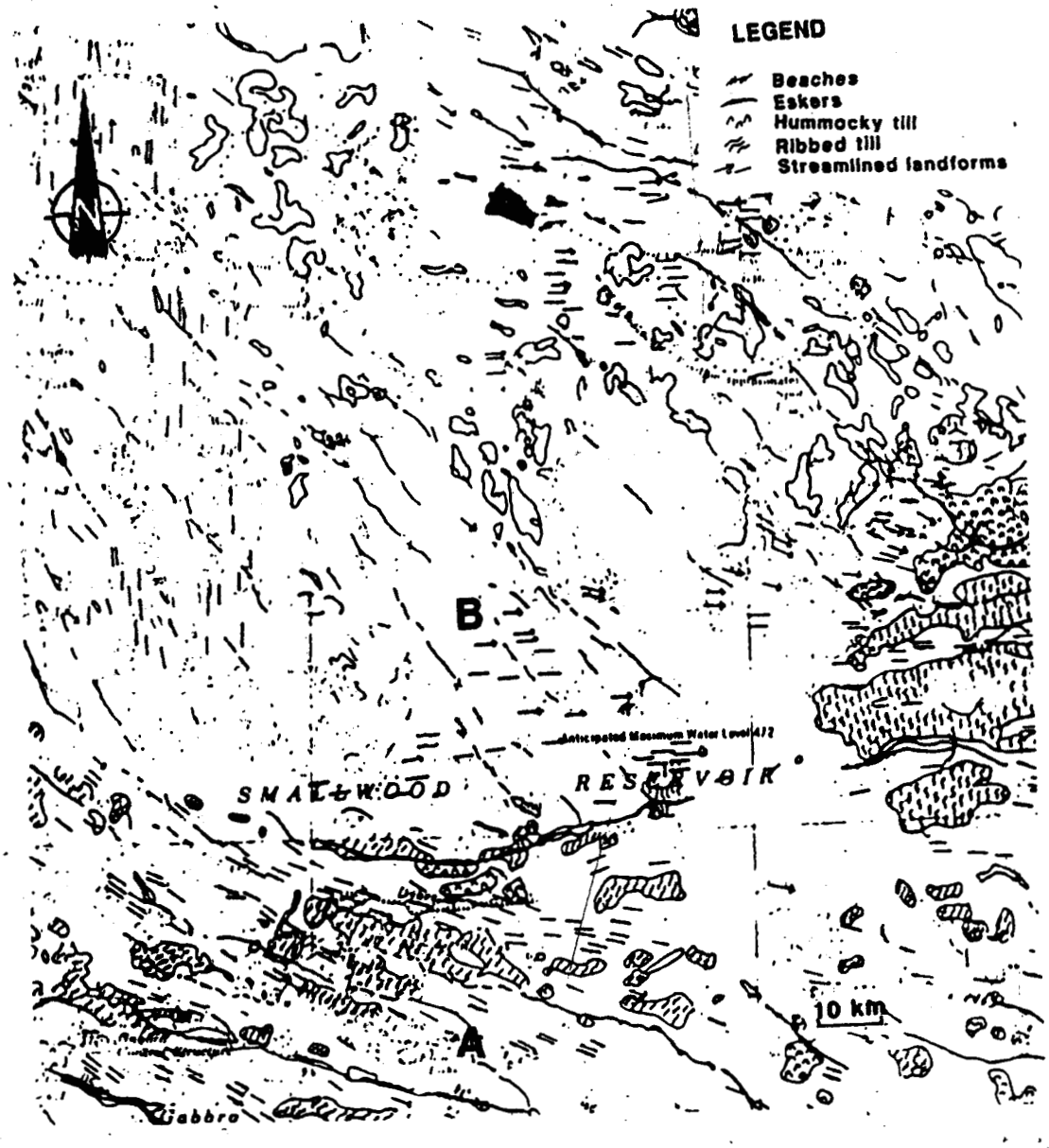


Figure 17. Orientation of eskers with respect to late ice flow, as recorded by fluted landforms. In general, eskers are sub-parallel to late ice flow (A), but may be up to 70° from it (B).

ice from the Smallwood Reservoir area, thus changing the glaciostatic gradient and inducing meltwater flow towards it, but not strong enough to reshape fluted landforms deposited during regional ice flow.

Eskers located in the «organized esker zone» are generally located in the margins of broad, <20-40 m deep, valleys of the Lake and George plateaus which usually parallel ice flow orientations. The modern valleys slope towards the coasts from the drainage divide, but during deglaciation, due to differential isostatic depression (about 1 m/km), meltwater flow was generally up-hill, driven by differential glaciostatic pressures in the overall ice flow direction. Where isolated hills are located across esker paths, eskers tend to go around the hill and then resume their original orientation (Fig. 18A). The scale and frequency of these bends has not been investigated, but for those eskers which have been mapped in detail the bends are infrequent, affect less than 5 km of esker length, and can be affected by local topography. Where ranges of hills are located across esker paths, especially at the modern drainage divide, eskers change their course to cross the adverse topography at a low pass (Fig. 18B). In the pass, eskers may be absent, but fluvially eroded areas of bedrock are present, and the esker typically reappears within a kilometre of the pass. Exceptions to this pattern of concordance of eskers with topography are found in the George River valley. The valley was transverse to ice flow, and eskers originating west of the valley lead into and out of it, climbing eastward more than 150 m in less than 5 km (Fig. 19). The implication is that the ice sheet had to be thick enough during the formation of those esker segments in the valley that meltwaters flowed across the valley, rather than ponded as a subglacial lake. Alternatively, the esker segments may indicate drainage into the valley from both sides, an indication that the esker path was in fact controlled by drainage northward along George River valley. The continuity of the esker systems supports eastward flow across the valley. Reversal of flow would have been expected to produce a gap in the ridge during reorganization of meltwater flow. Also, based on the absence of eskers in the steeply descending valleys near the Labrador Sea and Gulf of St. Lawrence coasts, it is unlikely that a ridge could have been built in valleys descending towards the George River by meltwaters flowing into it.

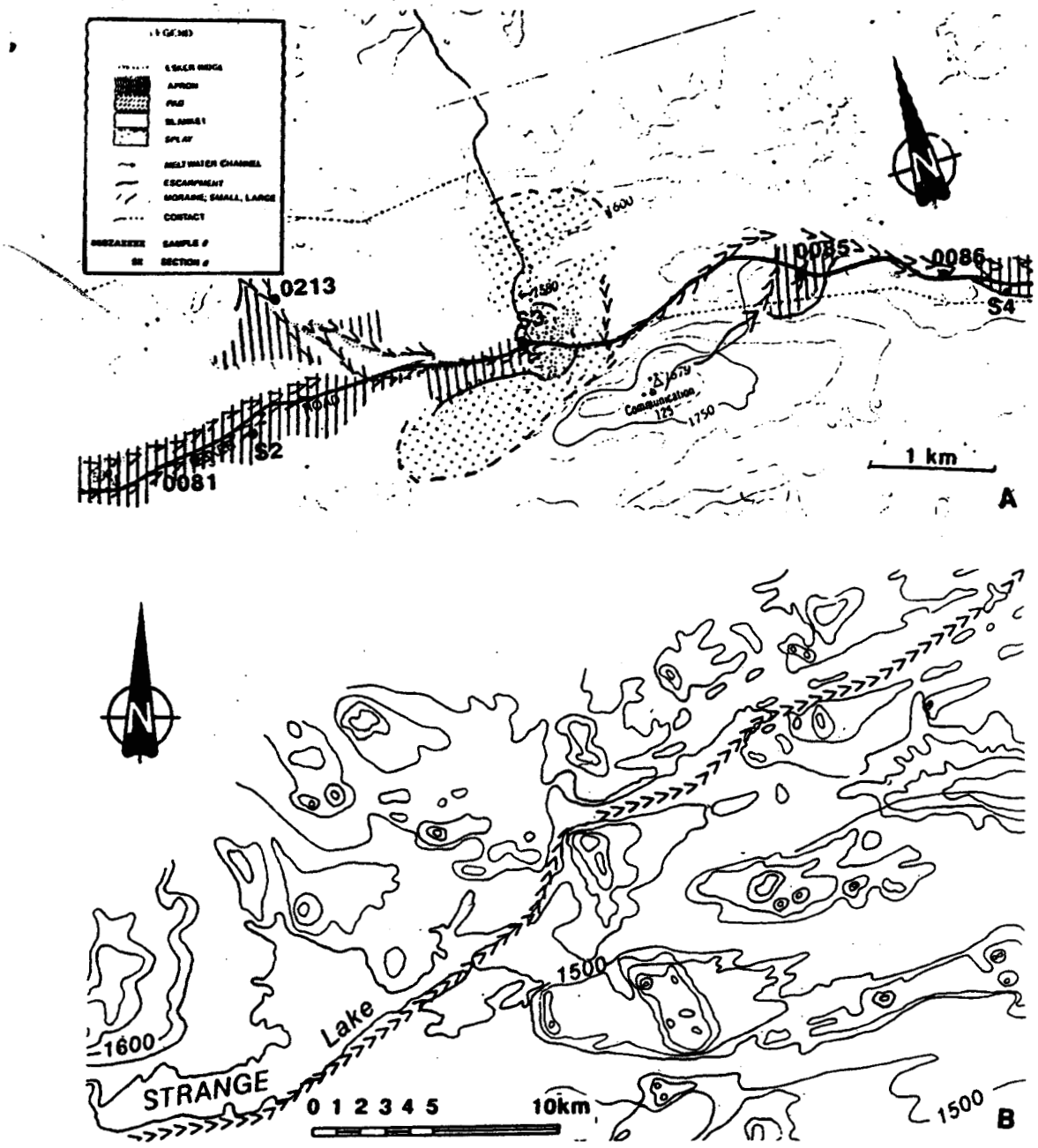


Figure 18. Relationship between eskers and topography. A) Esker paths go around isolated hills, and resume their original orientation on the other side of the hill. This is approximately km 40 of Gabbro esker. Contour interval is 50 ft. B) The path of eskers is modified to cross transverse high topography at low passes. This is approximately km 45 of Lac Brisson esker. Contour interval is 100 ft.

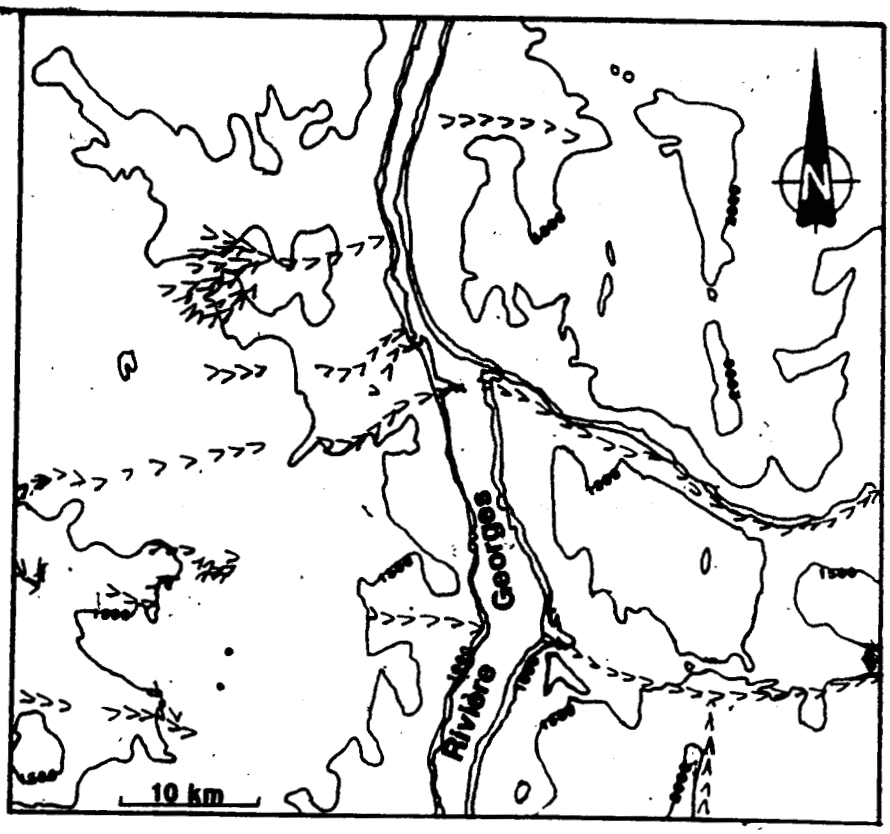


Figure 19. Eskers across George River valley. Eskers descend from the plateau on the western side of George River into the valley, and climb up onto the plateau east of it. Elevations are in feet asl. George River is at an elevation of about 300 m, while the plateaus on either side are at about 425-480 m.

(modified from Ives, 1960)

Organization of the meltwater drainage represented by esker systems

Within the «organized esker zone» esker systems are composed of a trunk esker, to which tributary eskers are «connected», either directly, or by meltwater channels or areas of bedrock presumed stripped of glacial debris by subglacial meltwater flow. Integrated esker systems (where short and long eskers, tributaries and trunk, are part of a subglacial drainage corridor) have second and third order streams (Plate 1). There may be up to 10 «tributaries» to a trunk esker, and each tributary may have a few lower order streams. Most trunk eskers, however, have relatively few tributaries, with only second and third order streams existing. The spacing between tributary junctions on the trunk esker is 10-50 km. Most longer tributaries are subparallel to the trunk esker, such that the drainage pattern is parallel. The apparent drainage pattern formed by eskers is similar to reticulate patterns defined by surface meltwater streams on the Greenland ice sheet (Sugden & John, 1976, p. 286), but at a scale one order of magnitude larger.

In northern Labrador, besides a few, short tributaries, usually less than three along each larger esker, there does not appear to be an integrated drainage pattern to the eskers. For those systems which are integrated, the length of the systems (in the overall direction of ice flow) is twice the width (taken perpendicular to ice flow) of the system. In central and western Labrador, most esker systems are composed of two long (>100 km) eskers to which up to 10 shorter (<40 km) tributaries are connected. Because of the two long eskers, the length (along ice flow) is up to seven times the width (across ice flow) of the system. In all cases, the shape of drainage basins approximates a rectangle (Fig. 20).

The paths of tributaries change notably a few kilometres from their junction with the trunk (Fig. 6, Plate 1). This is most apparent with longer tributaries, which are subparallel to trunk eskers for a long distance and are separated from the trunk by 10-15 km. Approximately 3-5 km from junctions with trunk eskers, the tributaries sharply bend, at an angle up to 90°, towards the trunk esker, and continue along the new path until it merges with the trunk. The angle of the bend does not appear related to the length of the tributary. Tributaries too small (<5 km long) to have a

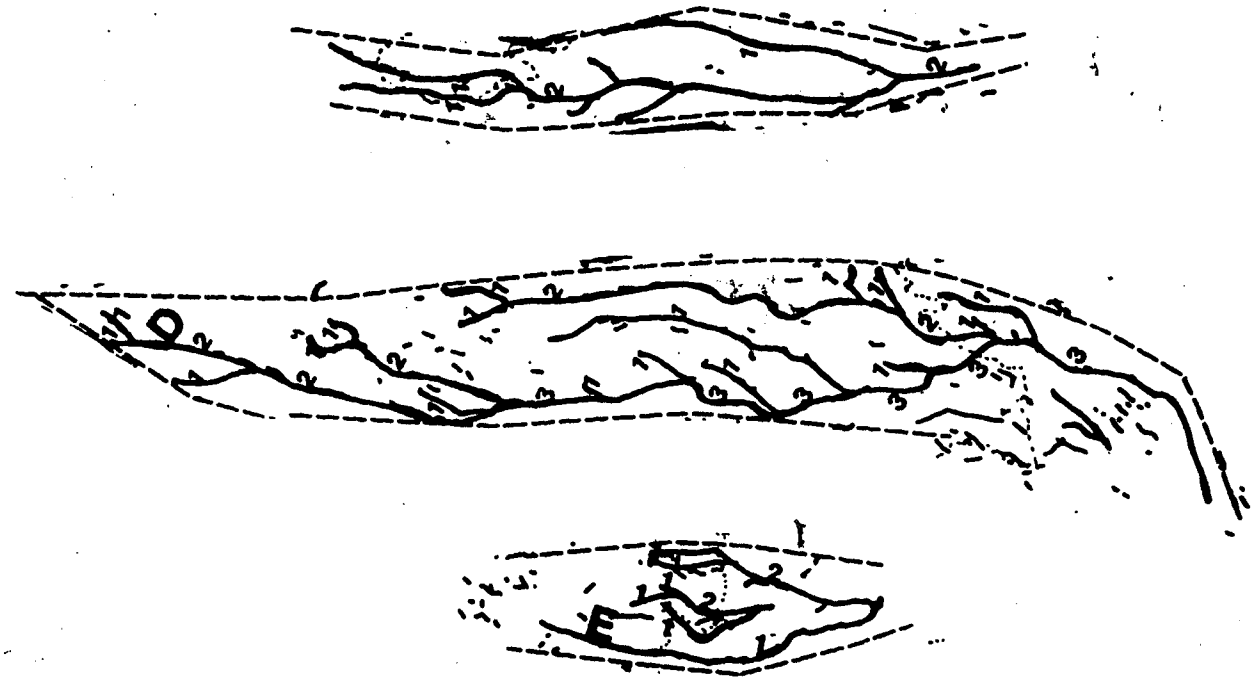


Figure 20. Drainage basin shapes. The examples given can be found on Plate 1. They are Ashuanipi esker (D) of western Labrador, Lac Brisson esker (E) of northern Labrador, and an unnamed esker west of Ashuanipi esker (top). The overall shape of each drainage basin is rectangular.

segment sub-parallel to the trunk, however, may not show this bend, as they already are at a large angle to the trunk. Most longer eskers, and some shorter ones also, appear to preferentially connect from the left (from the northeast for those eskers trending southeast). In the five systems studied, the junction is from the left (looking down-esker) for 30 tributaries out of 35, and the exceptions are usually very short (<5 km) eskers. Tributary esker junctions from the left have also been noted in Keewatin and there, they have been attributed to the Coriolis effect over a large featureless plain, such as the surface of an ice sheet (Aylsworth & Shilts, 1989).

The control over which esker is tributary to another does not appear to be related to the overall length of eskers. Long eskers may be tributary to smaller ones, the criteria to define a tributary being the «bend» that an esker has when it merges with another esker. Thus, the control on which esker is trunk and which is tributary must be the tunnel which has the most favourable meltwater drainage conditions, such as outlet through a lower valley. Based on the patterns of tributary eskers over most of Labrador, the hydraulic control appears to be most effective a few kilometres (3-5 km) away from the trunk esker, as that is from where the tributary modifies substantially its path.

Calculations by Hebrand and Åmark (1989) of the area of subglacial drainage needed to supply enough water for a discharge of 1 m^3 /s in a 10 m wide subglacial channel if the water came solely from 1 cm^3 /cm^2 a subglacial melting, indicates that it would be on the order of 600,000 km^2. For such flow velocities, the subglacial stream could not allow transport of debris larger than sand-size. The maximum size of drainage basins in Labrador is in the order of 15,000 km^2, and because the subglacial meltwater production was likely in the same order of magnitude in Labrador as that postulated for Sweden (1 cm^3 /cm^2 a), the discharge in subglacial tunnels in Labrador if the water was entirely subglacial would have been less than 0.1 cm^3 /s in a 10 m wide tunnel. It is likely that subglacial tunnels which handled only drainage of subglacial meltwaters directly in the drainage basin of an esker system were too small to form any eskers in Labrador. Thus, supraglacial and englacial meltwaters are necessary to account for the quantity of meltwater needed to transport the sediment

within the eskers they studied. Therefore, if the tunnel systems represented by eskers existed simultaneously during deglaciation, they could have handled the subglacial drainage of its drainage basin, without the capacity to form esker ridges. It is conceivable that englacial meltwaters, as well as supraglacial meltwaters, which eventually reached the basal tunnel system, were required so that the subglacial stream competence was enough to transport esker debris.

Discussion on esker distribution

In Labrador, most eskers are located in broad, gentle, well to ill-defined valleys, with an overall slope of 0.00004 - 0.0006, to negative slopes, before isostatic recovery, (Table 1; average correction of 1 m/km; Parent & Occhietti; 1988). Eskers are often located either along or within lakes and rivers, which they cross infrequently and do not substantially impound drainage. Eskers are not necessarily found at the lowest point of their valleys. Although the edge of the Labrador Trough, a local relief of about 330 m, may have had a supraglacial expression in the form of a broad depression on the ice surface, most other valleys are shallow (<20 m deep) and ill-defined, with, presumably, no corresponding supraglacial topography. Therefore, for esker paths to be locally controlled by subtle subglacial topography, the stream in which eskers formed must have been located at the base of the ice sheet and topographic effects must have been significant with respect to glaciostatic effects.

Superposition of the supraglacial drainage pattern on the subglacial system, much as a template, has been proposed by Shilts (1984) to explain the apparent branching of esker paths, and may even explain the apparent straightness of eskers, related to straight supraglacial streams on the steep ice margin. While supraglacial drainage may affect the subglacial system when it merges with it, the patterns of supraglacial drainage on modern ice sheets (Sugden & John, 1976, p. 286) are not at the same scale as esker paths imply the subglacial system to be. Supraglacial stream density appears to be much higher than esker systems, and more likely to change rapidly due to presence of crevasses, differential ice movement, etc..

While rivers are not directly analogous to meltwater streams, they provide a basis for comparison. Under conditions of low slopes and broad valleys, rivers are expected to develop a

meandering pattern, with sinuosity indices of 2 and higher. While a common description of an esker is of a sinuous ridge, all eskers studied in Labrador are straight, with an overall sinuosity index ranging between 1.05 to 1.1 (Table 1). Observation of low sinuosity modern streams show that these low sinuosity rivers often carry a coarse bed load (Ritter, 1978; p. 241). The straight nature of eskers may be partially related to the coarse load which is transported in the esker tunnel, analogous to modern fluvial systems.

The most important control on esker path and sinuosity, however, is likely the ice surface gradient which, especially near the ice margin where esker segments are presumed to be formed, is steep, as controlled by the velocity of the ice and the thickness of the glacier. Secondary control on esker path by subglacial topography affects segments of the tunnel where local conditions do not favour the overall orientation given by the ice surface gradient.

ESKER MORPHOLOGY

Esker ridge

Esker morphologies (Figs. 10, 15 and 21; Table 4; Appendix IV) most often seen in Labrador are the single ridge with steep flanks and a sharp crest, the double ridges, and the multiple ridges. Commonly, double and multiple ridges have a principal ridge which is higher and coarser grained than the others. All can have steep flanks and sharp crests. Eskers which have flat tops appear to have been modified by wave action when they were uncovered sub-aquatically, or by current action in a river-like environment between ice walls in an open tunnel at the margin of the glacier. In the systems which were studied more closely, single ridges represent 50-75% of the total esker length, double ridges are 0-20%, multiple ridges are 0-3%, while gaps account for 20-30% of total esker length. Ridges are 3-30 m high, and 30-350 m wide at the base. Esker complexes (including aprons, pads, and splays) are up to 1.5 km wide, while blankets of gravel can occur as much as 3-4 km on either side of the esker ridge (Table 1).

Eskers studied have a low overall sinuosity index (1.05-1.10, measured as the crest length over the straight line length from beginning to end) while individual segments range from straight

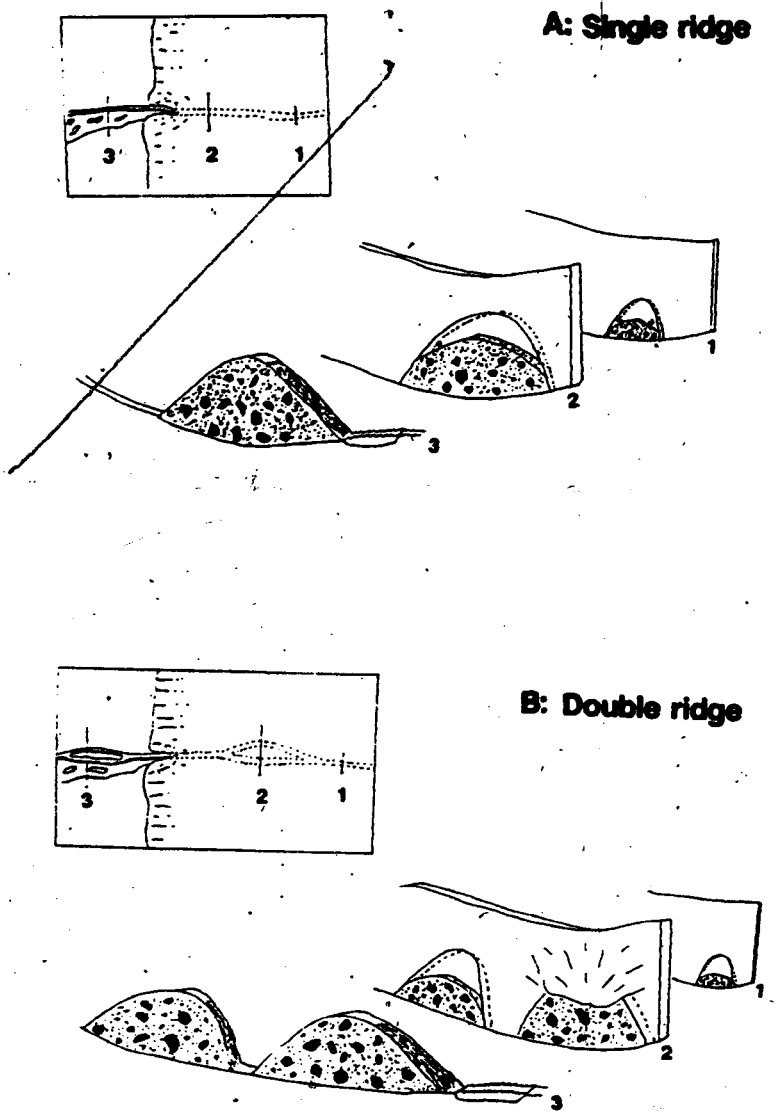


Figure 21. Model of formation of ridge morphologies. Ridges are tunnel deposits (A), and blockage of the main tunnel may induce formation of a secondary tunnel, thus leading to double-ridge segments (B).

Esker	Morphotypes, ridge				Morphotypes, associated deposits				
	Single	Double	Mult.	Gaps	Apron	Pad	Splay	Blanket	None
Gab.	63	16	0	21	62	12	6	36	11
Osak	49	19	3	28	35	31	14	29	23
Shabo	66	5	1	28	41	33	9	44	17
Ash	70	0	0	30	31	32	0	58	3
Lac B.	74	2	0	24	29	30	9	27	12

Table 4. Morphotypes for each esker systems, expressed as percent total length. Associated deposits can total more than 100%, since more than one associated deposit can be found along an esker segment. The percentage of esker length for which there are no associated deposits includes gaps in lakes. There are esker segments for which a ridge has not developped, but where there are associated deposits.

(SI=1.00) to moderately sinuous (SI=1.32). The low sinuosity may be related to the influence of the valleys in which eskers are often found. The subglacial tunnels meandered in the confines of the valleys, but did not spill over their edges. The most sinuous segments are found where eskers circle around hills or where they cross low points at divides. Sinuosity and other factors such as slope, may be related to ridge morphology. For example, Gabbro esker, which has the greatest proportion of single ridge segments (75%) is the straightest esker studied (SI=1.05), and also has the least negative slope (-0.0005, before isostatic recovery), except for the overall slope of Shabogamo and De Mille esker systems, which end in a valley leading to the St. Lawrence Estuary.

Two or more ridges can form as the result of blockage or collapse of the ice roof on an existing tunnel (Aylsworth and Shilts, 1989) (Fig. 21B) or due to changes in the glaciostatic load as meltwater is directed up gently ascending reaches (Shreve, 1985). The best example is Ossokmanuan esker, which has the most abundant double-crested and multiple-crested segments. Ossokmanuan esker has the most negative slope (not counting Lac Brisson esker because it has a short segment in the George River valley) of -0.0022 m/km. It has to be kept in mind that because of differential isostatic depression at the time of esker deposition, most esker segments in Labrador were deposited against adverse topography (Table 1).

The sharp crest and steep sides of the ridge may be primary features imposed by secondary water currents (Shreve, 1972) on either side of the ridge. The currents flowed up the ridge to the roof of the tunnel, and down the ice walls to the tunnel floor. The action of the water currents at the base of the ridge is to erode and transport the sediments up the ridge. The debris is deposited near the crest of the ridge where both up-currents on either side of the ridge converge. Alternatively, slumping of the sediment after melting of the sustaining ice walls can produce the same morphology. Slumping may be suspected if post-depositional faulting is identified in the ridge (eg. McDonald and Shilts, 1975). Faulting was not recognised in those eskers studied in Labrador, maybe because faulting can not be easily identified in coarse sediment.

Ridge morphology indicates that eskers were deposited in a subglacial tunnel, the position

of which, in the context of the ice sheet, was controlled by the presence of subglacial valleys. From the morphology, it is not possible to establish where in the tunnel (near the ice margin, a few km from the ice margin, or deep within the ice sheet) the esker was deposited, or how long a segment is deposited at any one time.

Associated deposits

Fluvioglacial sediments comprising esker systems, but not part of the ridge, are termed «associated deposits». They comprise four main landform types, termed: «aprons», «pads», «splays», and «blankets» (Figs. 15 and 22; Table 4; Appendices I and IV). They are deposited in an ice marginal or proglacial environment, commonly in contact with the ice. They can either be continuous along the esker ridge, or periodic in distribution. For the five eskers under study, aprons and blankets are found along 30-60% of esker length, pads along 12-33%, splays, 0-15%, none, 3-23% (Appendix IV; Table 4). Eskers may be flanked by none, one or a combination of these landforms, or by none. Some landforms, such as pads and blankets, may be found in areas where ridges have not developed, but generally along the path of fluvioglacial systems. Aprons, pads and blankets can be continuous over 10's of kms, while splays punctuate the esker ridge for segments up to 3-4 km long.

Aprons (Fig. 22A) are always in contact with the esker ridge, lapping onto half to two-thirds of its base. Ridges which have aprons have gentler side slopes than those which do not have aprons. Deposition of an apron is thought to occur in an immediate proglacial setting, where the meltwater stream debouches from the tunnel. In that position, the stream is no longer confined, or less confined if a reentrant at the ice margin has developed, and the stream spreads out on either or both sides of the ridge. Widening of the reentrant with time, and thus evolution of the stream, from nearly parallel to the ridge initially to away from the ridge, may be expected. Migration of the stream sideways with enlargement of the reentrant may also explain why aprons do not cover eskers entirely. Wide aprons may have an up-esker ice-contact slope, indicating standstill of the ice margin during sedimentation of a fan-like deposit which otherwise has the characteristics of an apron.

Pads (Fig. 22B) are flat, low, with respect to the esker ridge, landforms deposited in an

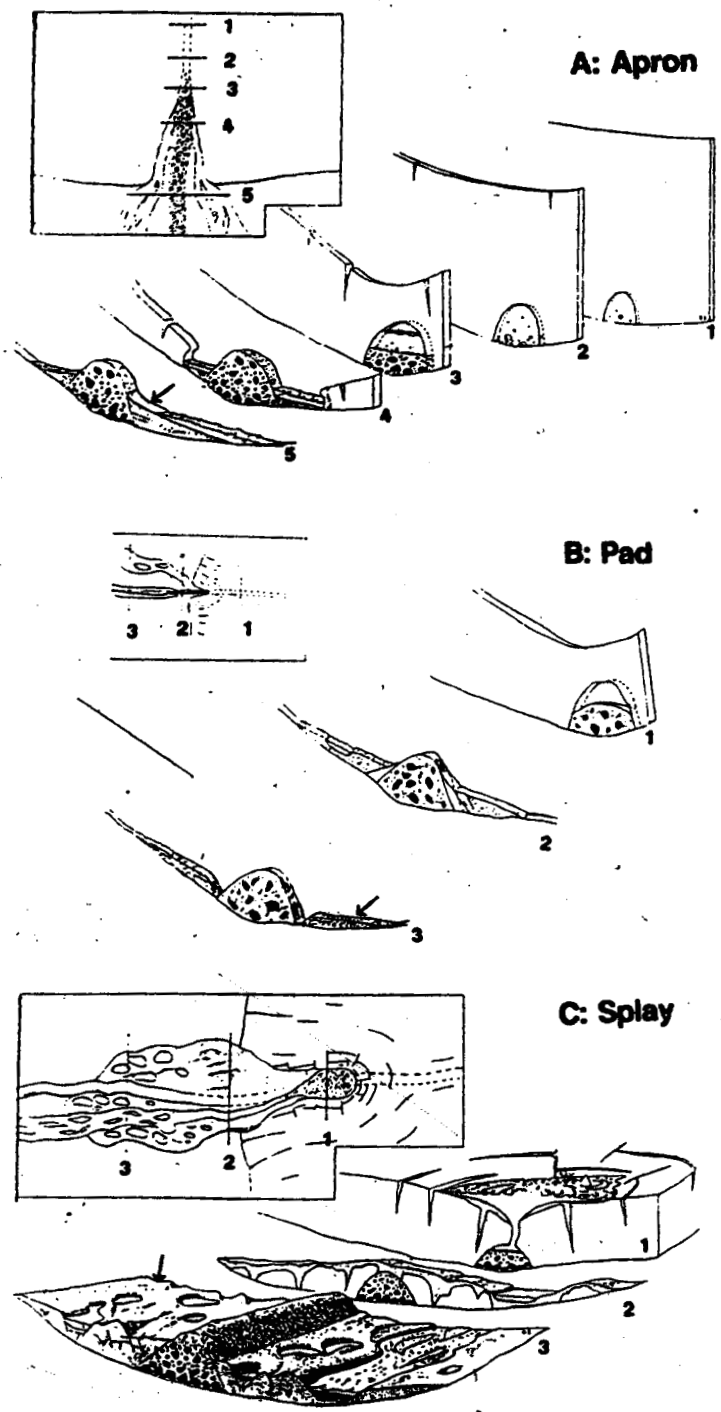


Figure 22. Model of formation of associated deposits. Associated deposits are sedimented in a proglacial or supraglacial position, after sedimentation of the esker ridge. Aprons (A), pads (B) and splays (C) are represented. The numbers represent different stages of formation of associated deposits. Arrows point to the resulting landform on each sketch. Blankets, which are not sketched here, result from unconfined sedimentation in a proglacial setting.

unconfined proglacial environment. Pads are adjacent to a ridge, typically separated from it by a shallow ditch that is likely an indication of the melting of buried sustaining ice walls. Pads may also be located as an extension of aprons, in which case the ditch is not present. Aprons which are continuous with pads may signify proglacial sedimentation for a period of time long enough to allow total unconfinement of the proglacial stream, and retreat of the reentrant in the ice margin.

Splays (Fig. 22C) are also low, with respect to the esker ridge, landforms, but differ from pads by the presence and abundance of kettles. The kettles imply that the splays formed over ice, in a proglacial or supraglacial position. The ice blocks may be present at the margin of the ice sheet in the stagnant zone, over which a glacial stream spreads out its fine-grained load. The deposit would then be expected to thin away from the ice margin, and to have an ice contact slope on its up-esker face. The fine-grained sediment may be deposited in a subglacial cavity, followed by collapse of the ice roof and subsequent filling by more fine-grained sediments from the now subaerial glacial stream. In this case, the deposit would be expected to be gradational in grain size to the esker ridge, which itself would not be as well defined as if it had been deposited in a narrow tunnel. The splay would also be thinning away from the ice margin, and may have an ice-contact up-esker face.

Since observations of the splay did not indicate a thinning of the landform downstream, and because ice-contact slopes are present not only on the upstream face, but around all edges of the deposit, another mechanism may have acted to form splays (Fig. 22C). Near the ice margin, where ice is less than 30-40 m thick, crevasses may reach to the base of the glacier. Deeper crevasses do not usually exist, since the ice is normally plastic enough to adjust to stresses by plastic deformation, rather than by crevassing (Sugden & John, 1976, p. 74). Similarly, most moulins on modern glaciers have been found to be between 25 and 30 m deep (Sugden & John, 1976, p. 289). A subglacial stream may be diverted up through a fountain, which would deposit fine grained sediment carried up with the flow in a bowl-shape depression at the surface of the glacier. Upon melting of the underlying ice, kettles and ice-contact slopes would result. Because the connection of a fountain to the subglacial tunnel system is a random event which only persists until the ice margin has retreated past the

fountain, splays are not expected to be located continuously along the esker, but be present along limited segments of the ridge.

Blankets are composed of sand and gravel deposited on top of previously deposited glacial deposits and can be thick enough to completely mask underlying morphology. More typically, blankets are found on top of ribbed moraine, especially in western Labrador along Shabogamo and Ashuanipi eskers. Blankets can be found in contact with till with wich it progressively merges (no steep margins), and are likely the result of unconfined sedimentation in a proglacial environment.

Discussion of esker and associated deposits morphotypes

The morphology of eskers indicates that ice is present during their formation, that it is thin (<30-40 m thick, to allow crevasses and moulins to reach to the base of the glacier, and to allow subtle subglacial topography to play an important role on the paths of eskers), and that the esker tunnel (in which esker deposition is taking place) terminates at the ice sheet margin, in order for aprons and pads to be deposited. While deposition of the esker ridge and of the associated deposit is not synchronous, glaciological considerations indicate that formation of the ridge occurs near the ice margin where the subglacial tunnel can enlarge by frictional melting and not be closed by ice creep. Only in an enlarged tunnel, or if water velocities otherwise decrease, can deposition of the esker ridge happen.

The only indication from the data collected in this study that subglacial tunnels penetrate deeply inside the ice sheet, is the presence of esker segments on both sides of the George River valley in Nouveau Québec, a local relief of about 150 m (330 m from bottom of the valley to top of the hills on either side). If esker paths are affected by gentle topography when the ice is thin, then ice has to be thick for esker paths to not be affected by a major topographic feature. The glaciostatic gradient in such a situation would have induced high water flows in the tunnel, but not deposition of sediments. Along Lac Brisson esker, there are no indications of meltwater escape routes which could have handled a large amount of fast flowing subglacial meltwaters except near its easternmost end, at the head of Anaktalik Brook. There, numerous meltwater channels cut in till attest to a major

drainage event. If that is indeed the position of the ice margin at the time a tunnel was present across the George River, then, using Nye's equation as a rough approximation of ice thickness (Sugden & John, 1976, p. 59), the ice thickness over George River might have been in the order of 1500 m, about 100 km from the ice margin. A 100 km long tunnel may not have had sediment deposited along its whole length, but it is likely that in this particular case (Lac Brisson esker), esker segments were formed at an early stage, far back into the tunnel, when the glacier was still thick, in order to keep the hydraulic head necessary to drive water up the George River valley side. This example may serve to emphasize how much local conditions are important in the development of particular esker segments.

ESKER STRATIGRAPHY

Esker ridge

Limited exposure and the coarse-grained character of the sediments made examination of sedimentary structures extremely difficult, and a statistical approach was used to determine likely patterns in sedimentation and draw inferences as to depositional sequences. The stratigraphic information was described using «units», defined as a layer of sediment of comparable character, *i.e.* sediment size, roundness, and type and abundance of matrix, which may represent one depositional event in the formation of eskers. In 72 sections located in esker ridges, sediments comprise beds ranging from less than 0.10 m to 10 m thick with grain sizes ranging from silt to boulders up to 1 m in diameter (Fig. 23A; Appendix V). Units are, in decreasing order of relative importance (relative to total thickness): fine mix unit (M_f, 47% of total measured thickness); medium mix unit (M_m, 11%); clast-supported units (cobbles, C_c, and boulders, C_b,: 10% each; pebbles, C_p,: 7%); sand (S, 8%); very fine mix unit (M_{vf}, 3%); diamicton unit (T, 2%); coarse mix unit (M_c, 1%); and silt and clay unit (SC, <1%). In the esker ridge, there is a lack of well developed, small scale sedimentary structures, such as ripple marks, laminations, thin bedding, although the scale of exposure (1 m wide sections uncovered) may not have allowed their recognition. There is, however, a crude layering, which is at times defined by a very well developed 1-1.5 m thick unit composed primarily of boulder-supported

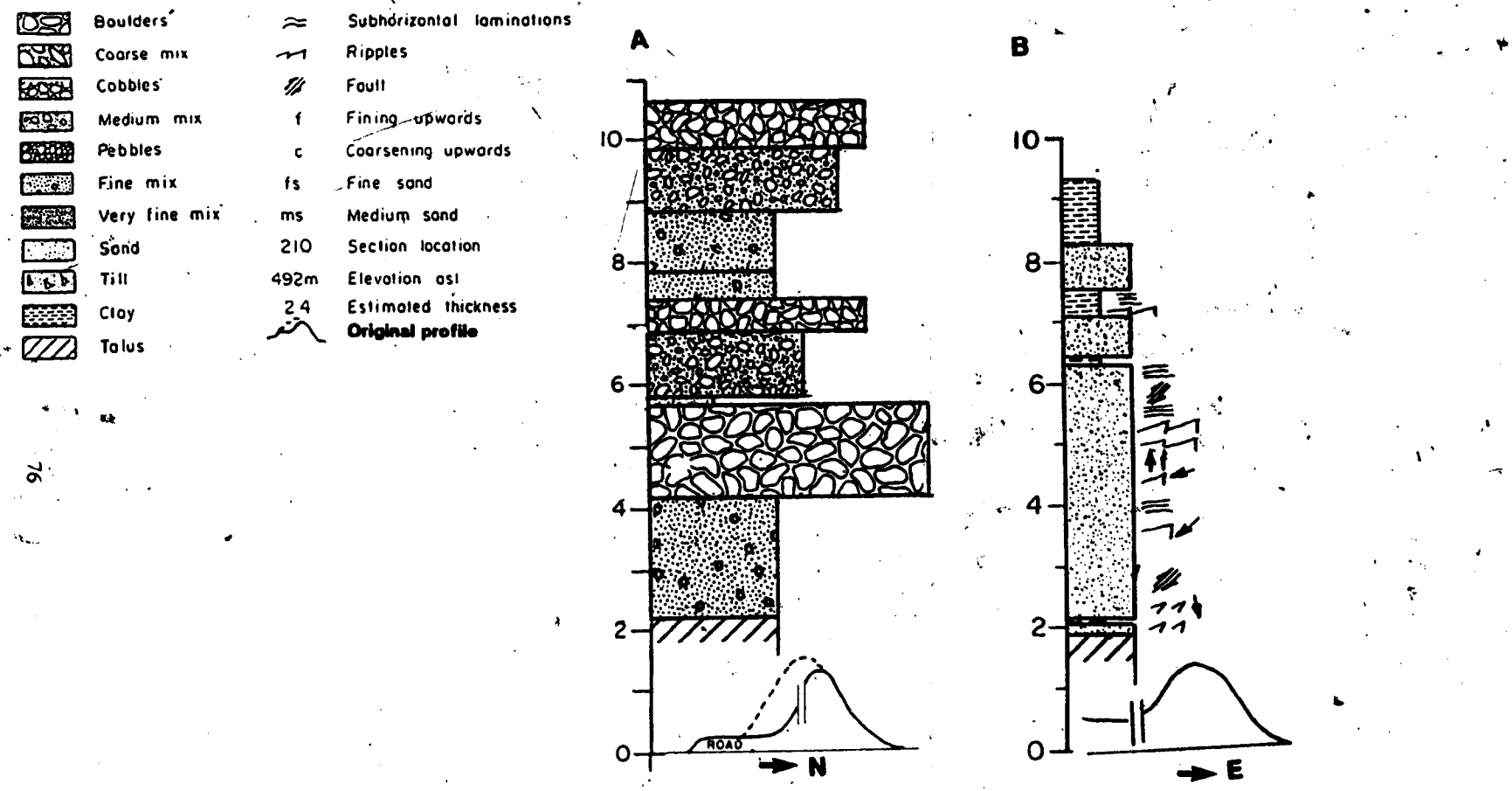


Figure 23. Esker and associated deposits stratigraphy. A) Typical section in an esker ridge (km 60 of Gabbro esker), showing the boulder bed (at 5 m) and cobble-supported units (at 7 and 10 m) which may be analogous to the boulder bed, with smaller size clasts. B) Typical section through associated deposits (km 18 of Moose Head esker, apron).

gravel. This structure is here called «the boulder bed» and is coded as C_b in the stratigraphic summaries of Appendix V.

The fine mix unit is massive to faintly stratified, rarely fining upwards (clast size), ranging in thickness from 0.20 to 8 m. The fine mix unit is normally massive. The matrix is composed of fine to coarse sand, with or without granules. Pebbles up to 7 cm occur disseminated in the unit or in discrete lenses. As a minor component, larger clasts may be present throughout the unit or concentrated at the base. The clasts are rounded to well rounded, rarely subangular. The unit is loosely to well packed. The fine mix unit is found most often at the base of sections, and therefore, the maximum thickness reported is a minimum estimate, as the lower contact was not uncovered in all cases.

Medium mix unit (0.2 to 1.5 m beds, exceptionally 4 m and 10 m thick) and coarse mix unit (0.5 to 1.3 m beds) are similar to the fine mix unit in that they are a matrix-supported, heterogeneous mixture of sand and clasts, but the size fraction of the clasts (cobble, 5-25 cm for the medium mix; boulder >25 cm for the coarse mix) are larger than for the fine mix unit. Each unit may have a minor amount of clasts smaller or larger than the unit descriptor. The matrix of the coarse mix and the medium mix units can be composed of anything smaller than the clasts, although coarse sand to granules is most common. The number of clasts in these units is at times great enough that some clasts touch, forming partial support to the unit. The units are massive to faintly stratified, and are loosely to moderately packed. The medium mix unit is found mostly towards the base of exposures, while the coarse mix unit is found independently towards the base or the top of sections.

Clast-supported units, (boulders: 0.3 to 2 m beds; cobbles: 0.1 to 2 m beds and pebbles: 0.05 to 2.5 m beds) are essentially similar in that they are composed of clasts forming the framework of the unit, between which a sandy matrix can be found. The basic difference between clast-supported units is in the size fraction (boulders: >25 cm diameter; cobbles: 5-25 cm diameter; and pebbles: 1-5 cm) involved. The clasts may be imbricated, and range from loosely packed to tightly packed. Matrix, when present, is composed of fine to coarse sand, with or without granules. Some clasts, other than

the descriptor, may be included, in minor quantities, in each category. Clast-supported units are massive to faintly stratified, and may coarsen or fine upwards. They tend to be found towards the top of exposures.

Undifferentiated sand units (0.05 to 3 m beds) are massive to laminated, and may have a few clasts. Some beds may coarsen or fine upwards. The sand units in the esker ridge do not appear to be located preferentially at the base or the top of exposures. The very fine mix unit (0.1 to 3 m beds) is found towards the base of exposures and are composed of small pebbles, 0.5 to 1 cm in size, with a sand matrix and may have a minor amount of small pebbles. The very fine mix unit is massive to faintly stratified, and may coarsen upwards. Two units of silt and clay, each 0.2 m thick, laminated with sand, and seven diamicton units, most likely till, 0.5 to 1 m in thickness, have been recognized. The diamicton units, till, have a silty matrix with subangular pebbles, and are massive. Diamictons are found towards the base of exposures, although not necessarily as the basal unit.

The bulk of esker sediments are mixed sizes, *i.e.* pebbles in a coarse sand to granule matrix. Typically, sections through the ridge show an alternation from a pebbly gravel to a cobbly-bouldery gravel, clast-supported or matrix-supported. In longitudinal sections the continuity of some beds over a few hundred meters can be observed, but the most characteristic features is the abrupt changes in the nature of the sediment between adjacent sections.

In eskers, small scale sedimentary structures were not observed, except for some laminations in sandy sediments. The most characteristic feature observed is «the boulder bed». It is present in 27 sections as one, rarely two, layer(s) per section and is commonly located half-way to two thirds of the way up from the estimated base of the esker ridge. Cobble-supported and boulder-supported layers are present in 49 sections in up to three distinct layers. The longitudinal continuity of the boulder bed could not be assessed, as very few longitudinal sections are exposed, but is estimated to be in the order of a few hundred meters long, and found sporadically along the esker. There is, however, a distinct change in the character of the sediment above and below the boulder bed. The change in grain size is abrupt, usually from a mixed unit with pebbles or cobbles below the boulder

bed, to the boulder bed, to a fine mix or sand unit above the boulder bed.

Besides the boulder bed, crude, subhorizontal layering within units defined by subtle changes in clast sizes (not large enough to change the category of the descriptor) or weak alignment of pebbles (long axis orientation parallel to the ridge, dipping up-esker), was also observed. Other apparent layering in the sediment pile was defined by the changes in sedimentary units.

Treating the stratigraphic data with the upwards transition matrix statistical technique described in Appendix VI, the most characteristic esker ridge sequence may be constructed, based on relative stratigraphic positions of units within eskers, average unit thicknesses, and the most common upwards transitions. The data suggest that an esker would start with a fine mix or a medium mix unit, followed by clast-supported units (cobbles, then pebbles), a sand unit, then a pebble-supported unit again. If there was continuous deposition in an esker tunnel during its «life», *i.e.* from the time deposition was initiated to the time the esker was uncovered, the sequence depicted $M_f \rightarrow C_c \rightarrow C_p \rightarrow S \rightarrow C_p$ might be a reasonable approximation of the sedimentation cycle. If the sequence was found superposed a number of times in sections, then it might indicate yearly sedimentation. In a subglacial stream, however, daily and seasonal meltwater input fluctuations are likely to produce high capacity, high competence streams which may be responsible for erosion of especially fine-grained units or modification of deposited sediments, such as winnowing of fine debris in coarse-grained units.

The sequence suggested by the statistics is supported by field observations, but is not complete because it does not take into account the presence of the boulder bed, which has been identified as one of the «most striking» features of esker ridges. The boulder bed may well be more apparent than statistically important. The boulder bed is not found preferentially above or below any other unit, at a frequency that is statistically significant. Either the boulder bed is the result more sections, in which the boulder bed is present, need to be described in order establish statistical significance. Based on field observations, the boulder bed is the result of a random catastrophic event for which there are no precursors left in the sedimentary record, during which large clasts were available, either in the ice, as a debris band, or in already deposited sediments. The catastrophic event may be spring thaw,

during which the subglacial stream is energetic enough to erode boulders out of the ice and transport them some distance. Once the boulder bed is emplaced, it is followed by an episode of quieter sedimentation, during which deposition follows a sequence similar to that described above.

Associated deposits

In associated deposits, 18 sections were investigated (Appendix V, Fig. 23B), some of which also exposed the esker ridge. Nine sections are located in aprons, six in pads, two in blankets and one in a splay. Undifferentiated sand units amount for 60% of total measured thickness. The fine mix unit (11%), cobble-supported gravel (10%), silt-clay units (9%) are almost equally abundant, while diamicton (5%), very fine mix units (3%), medium mix units (2%) and pebble units (1%) are less abundant. In associated deposits, the coarser units are most often found at the base, which may indicate that the fine-grained appearance of the deposits is only superficial, or that the associated deposit is thin and underneath it, the section uncovered the coarse esker. Sand units and silt-clay units have special characteristics in associated deposits which are different from the same units found in the esker ridge, and will be described in subsequent paragraphs. All other sediments in associated deposits are similar to their equivalents in esker ridges, and will not be discussed further.

Sand beds are 0.02 m to 8 m thick, and may be rhythmically laminated with silt and clay. Syndepositional sedimentary structures in sand are laminations interpreted to be related to the upper flow regime and climbing ripple cross-laminations. While the orientation of climbing ripples is erratic in most cases, in two locations in western Labrador, it suggested unconfinment of the proglacial meltwater stream which built the apron in which the ripples were found. At the base of the sections, ripples were oriented sub-parallel to the esker ridge, while orientations farther up the section were at a progressively higher angle (up to 90°) to the ridge. Post-depositional structures in sand are 1- normal faults indicating slumping, 2- reverse faults indicating rearrangement of the sediment into the cavity left by the melting of buried ice, and 3- ball and pillow structures indicating rapid dewatering of the sediment.

Most silt and clay beds (0.02 m to 1 m) are associated with rhythmically laminated sand and

silt-clay, which form packages up to 1 m in thickness, with individual layers 1-2 cm thick, and up to 10 cm thick. Silt-clay beds may be found to drape over underlying ripples in sand. All rhythmically laminated sand-silt packages are associated with the presence of former glacial lakes in western Labrador, which were dammed up against the watershed. The water depth may have been in the order of 10 m, based on the elevation of the lowest point on the watershed and the position of the rhythmically bedded sediments. Moose Head esker, with which rhythmites are associated, does not appear to have been reworked by wave action, as it retains its sharp crest.

Because there are few sections of associated deposits, the upwards transition statistical technique does not yield as detailed information as desired. Because some of the sections described associated deposits in contact with the esker ridge, the most probable transitions picked out in the tested residual are really applicable to the subjacent esker ridge ($M_r \rightarrow C_b$, C_c or C_p). The most probable transitions in associated deposits *per se* is S → M_m or SC, and SC → S, which is mostly characteristic of those sections with rhythmites located in western Labrador.

Nevertheless, the sediments found in associated deposits are indicative of an environment of deposition less confined than the esker ridge, i.e. a proglacial rather than subglacial environment. The position of the associated deposit sequence, especially the apron, with respect to the esker ridge sequence, indicates that the sedimentation of associated deposits postdates that of eskers, and that equivalent size material will have been transported farther in associated deposits than in esker ridges. Syndepositional sedimentary structures (laminations and climbing ripples) indicate a variable flow regime with the stream flowing at or above its maximum capacity. Post-depositional structures (faults) indicate that associated deposits were sedimented in contact with ice and even buried dead ice.

Discussion of esker and associated deposits stratigraphy

In all Labrador eskers for which there is stratigraphic information, there is a set of sedimentary units characteristic of the esker ridge (Fig. 24), and another of the associated deposits (Fig. 24). Within the ridge, the fine mix unit is, by far, most abundant. It is likely, therefore, that the environment of deposition of the fine mix unit is the most characteristic. Within associated deposits,

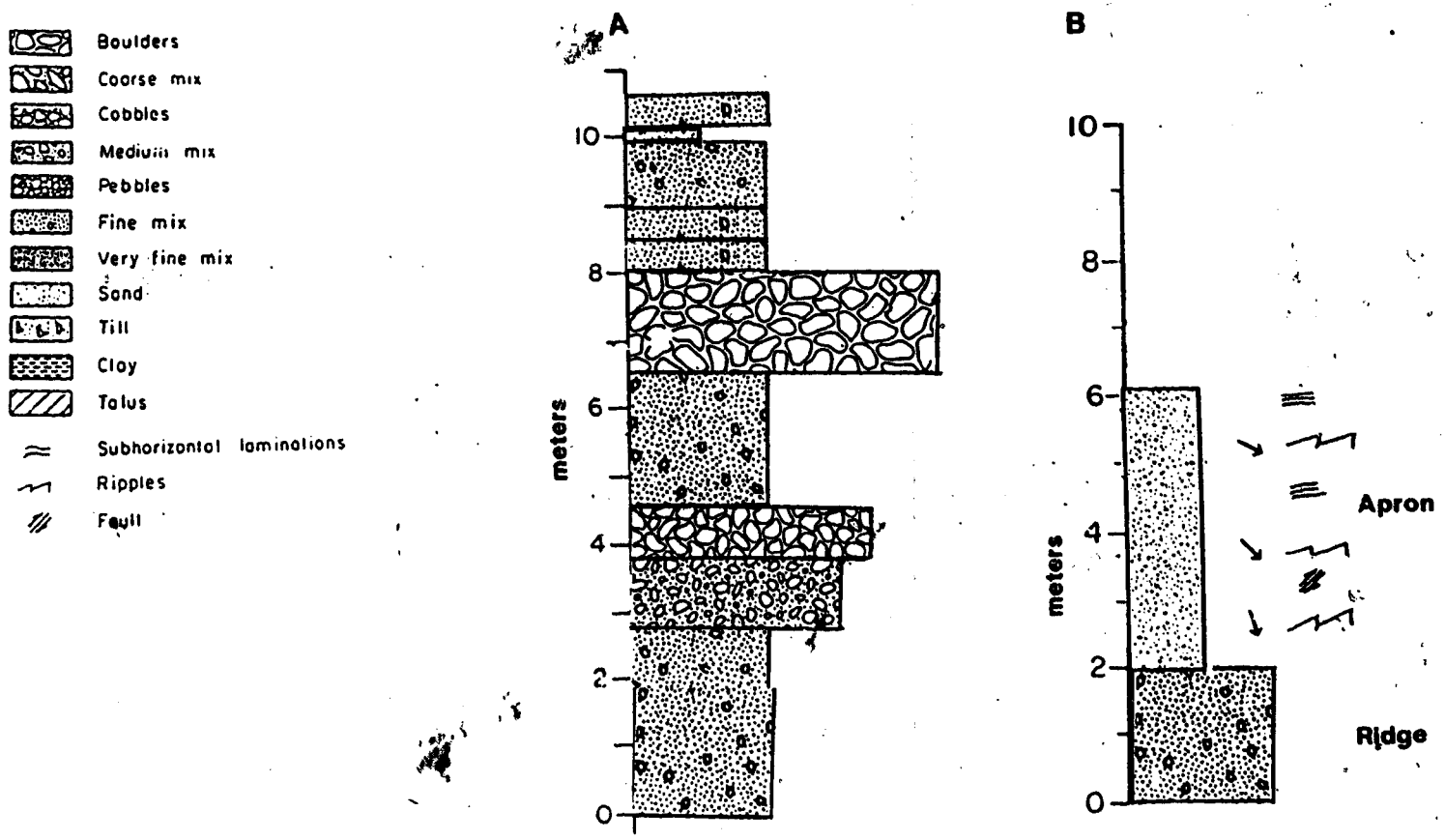


Figure 24. «Type» stratigraphic sections for the esker ridge (A) and associated deposits, apron (B). In the esker ridge, the fine mix unit is the most abundant and there is a boulder bed at about 2/3 up the section. In the apron, the sand unit is in contact with the esker ridge, paleocurrents indicate an unconfinment of the proglacial stream, and there is post-depositional faulting.

the sand unit is the most important. Again, its environment of deposition is likely to be characteristic of the environment of deposition of associated deposits. Till, which can occur at the base of eskers or associated deposits, is genetically independent from esker sediments. Its presence, however, implies that either the esker tunnel did not reach to the base of the ice, or that the energy of the meltwater stream was not high enough to erode the till. Because esker sediments overlying till, where observed, were not finer-grained than the till, it is more likely that the esker tunnel did not reach to the base of the ice.

Esker debris is derived from till and englacial debris. If coarse sediment is not present in till, then the esker can only be composed of fine-grained material, even though the competence of the stream may be high enough to transport coarse particles. In Labrador, the till is sandy, with some silt and clay size particles, and an abundance of large erratics found mostly on the surface. The blocks can be from 0.5 to 3-4 m in diameter. In eskers, the maximum size is about 1-1.5 m in diameter, which indicates that either larger boulders are not transported by meltwater streams, or that they rapidly break to smaller sizes.

The mixed units are composed of all size fractions, and clasts are surrounded by matrix, indicating simultaneous transport and deposition of matrix and clasts. The mixed units found in an esker ridge may have been transported and deposited as a sliding bed such as has been described by Saunderson (1977, 1982). Studies have shown that flow velocities required to entrain coarse particles from a mixed bed are lower than if the bed was composed solely of that size fraction, and conversely, fine particles require higher velocities to be entrained from a mixed bed than from a uniform bed (Komar, 1987; Andrews, 1983; and others, cited in these papers). Entrainment of all particles in a sliding bed (Saunderson, 1977) of the mixed units requires progressively stronger flows.

The formation of a sliding bed is favoured by a high concentration of sediments, as is expected in an esker tunnel, a «low» velocity, but enough to carry all grain sizes involved, and a small drag coefficient, obtained by the buoyant effect of sand on coarse gravel, and seepage flow that «fluidizes» the sediment (Saunderson, 1977). Seepage flow occurs because in a subglacial tunnel flowing full,

water which would have formed waves is forced downwards into the sediment. The load is deposited when flow velocities decrease such that the bed can no longer be carried, as would happen where the tunnel is enlarged near the ice margin. Deposition decreases the cross-section of tunnel available for water flow, which has the effect of increasing flow velocities. If flow velocities increase sufficiently, and erosion of the tunnel ice ceiling by frictional melting is not fast enough, the bed will start to flow again. The process of deposition and re-entrainment may be self-maintaining over long distances (Saunderson, 1977). Flow conditions favourable for sliding bed transport would probably exist throughout the summer season, after high discharge events related to spring thaw have taken place. Deposition is likely to occur in late fall and early winter, when meltwater supply from the surface of the ice sheet is shut off by freezing.

Close to the edge of the ice sheet, subglacial meltwater may not be produced, or, if it is, may freeze in the tunnel as cold air from outside penetrates in the open and only partly filled tunnel. The glacier toe may also be frozen to its base by a penetrating cold front during the winter. Icing of deposited sediments could armour a season's deposit to preserve it during the next spring high discharge event, as it will take some time before all ice is melted and frozen sediments thawed and available for erosion and transport. Winter flow further up-tunnel, which would only come from subglacial melting, may not have enough energy to carry sediments en bloc, but may be responsible for winnowing of fine particles from a deposited mixed unit. An armoured bed of coarse particles formed by the selective removal of fine debris would result (Komar, 1987), which would require very high energy flows to re-entrain. If not re-entrained, the armoured bed would serve as a protective layer against erosion of all debris located below it. Icing is likely more important near the glacier margin than near the origin of the eskers, but it could not be assessed from the stratigraphic data collected.

Winnowing of fine particles during the winter may concentrate the coarse debris necessary to form, during the next spring high discharge event, the most striking stratigraphic feature of eskers: a layer, a few meters thick at the most, of well rounded, coarse cobbles to boulders (up to 50 - 70 cm

in diameter), called the «boulder bed». Where boulder beds were observed, they were located in steep-sided and sharp-crested esker segments associated with deposition in a subglacial tunnel. The water flow conditions responsible for the deposition of boulder beds were controlled by the interaction between widening of the tunnel due to frictional melting, and narrowing due to ice creep. Just before spring thaw, the subglacial tunnel is at its narrowest, and the input of water from snow melt, coupled with a narrow tunnel, generates high energy flows which can mobilize and transport boulders. Widening of the tunnel by frictional melting to evacuate all meltwaters occurs within a few days (Shreve, 1972; Drewry, 1986; p. 20). The increased width of the tunnel, the possibly lower input of water after most of the melt has been evacuated, yields lower velocity flows, during which the large particles are deposited, and the rest of the debris is carried as bed load.

During transport, rounding and size reduction occurs rapidly for large sizes (Schumm & Stevens, 1973). Boulders, if exposed to the flow, even if not moving, can be abraded in place (Schumm & Stevens; 1973). Abrasion is enhanced by breakage, chipping and fracturing suffered by boulders during transport. Thus, boulder beds, although transported for short distances, have to be deposited fairly rapidly and buried, in order to keep their large size. Boulders observed in sections were rounded to well rounded, and there was no evidence of breakage from particle collisions. The combined processes of breakage and rounding during transport and abrasion in place, act on size reduction and rounding of large clasts.

If large clasts are not constantly replaced by more large clasts, the deposit will rapidly fine down-esker, and coarse particles will no longer be part of the deposit. Replenishment of cobbles and boulders can come from melting of the ice roof and walls, and may only be episodic, as the factors controlling the location of large debris in the glacier are varied, including underlying bedrock topography and regelation of debris at the base of the ice sheet.

Gravel units which are composed of smaller clasts than boulders and large cobbles, may be the result of a mobile bed phenomena in which the finer particles are carried faster than the coarser ones, as they ride higher up in the load where velocities are slightly higher (Andrews; 1983). It is

expected that the matrix component of gravel layers transported as mobile beds would be fairly high, and that clasts would not be imbricated. The longitudinal discontinuity of gravel layers may be related to the non-replacement of coarse debris as it undergoes attrition, and to transport as bedload sheets (Whiting et al, 1988).

The bedload sheets proposed by Whiting et al (1988) for the transport of coarse sand and fine gravel in river beds may provide an analog for the presence of gravel layers in esker deposits. The bedload sheets are only a few coarse grains high, while they are much longer, up to 200 - 300 times the size of the coarse debris. For esker sedimentation, gravel layers, especially boulder beds, could be up to 2 m thick, and up to 200 - 300 m long, if they were transported and deposited as bedload sheets. In a bedload sheet, coarse particles that are in transport at the bed of a stream are slowed and stopped by other large particles already stopped. Finer sediments get trapped in the interstices between clasts, causing the coarse particles to be mobile again (Whiting et al, 1988). The bedload sheet is coarser and thicker at its leading edge. While breakage and abrasion of coarse particles should occur during the transport of bedload sheets, it has not been reported (Whitting *et al*, 1988). If breakage and abrasion are minor during the transport of bedload sheets, the sheets are fundamentally different from debris resulting from abrasion and breakage of coarse clasts, which produces a deposit which fines downstream (Andrews, 1983). The migration of bedload sheets is due to an inherent instability associated with the interaction between different size fractions during bedload transport (Whiting et al, 1988). Provided the bed is not fluidized to form a sliding bed, and that armouring from either selective entrainment or a mobile bed does not occur, the bedload sheets provide a mechanism for the relatively thin, compared to the whole deposit, coarse units.

Boulder beds are probably associated with infrequent high discharge events which would be the only ones able to transport such a coarse fraction. The high discharge events could be related to spring thaw, or to the connection of the supraglacial meltwater system to the subglacial system via moulins. If boulder beds are associated with spring thaw, it is conceivable that they should occur vertically periodically in the deposit, if sedimentation of an esker section continues over a number of

years, provided boulders are available. A boulder bed may be transported short distances every year, until its final deposition, which is why boulder beds are not found at any one section more than once or twice. The presence of only one boulder bed at a section may be because boulder beds are the result of merging of supraglacial meltwater to the subglacial system. The location of the boulder bed in the upper half of the esker may indicate that the ice sheet had to be thin enough to allow the penetration of moulins to its base. The discharge generated by the flow of both systems together would presumably last for a longer period than spring thaw, allowing the transport of a boulder bed and its deposition during the following fall.

Within an esker ridge, sand units can most commonly form a surface «cap» on top of the ridge. Deposition of a sand cap can occur after the esker has emerged from underneath an ice sheet, as an outwash plain is deposited in front of the glacier. As buried ice melts, the outwash plain is lowered, and the esker ridge stands out, as seen by Howarth (1971), in front of Breidamerkurjökull, in Iceland. Other sand units present in the esker ridge must have been the result of sedimentation during low discharge events, followed by protection from erosion of the sand, probably by freezing. Once the sand is buried by other units, it is then protected from further erosion.

The most represented unit in the associated deposits is sand, which may or not be laminated, or rippled, as primary structures, and may have high angle reverse and normal faults as secondary structures. The ripples seen in the associated deposits are climbing ripples, which indicate a high sediment load and «low» velocity with respect to the velocities attained in the tunnel. In the few places where the orientation of ripples could be measured, they suggested a diversion of the flow away from the ridge upwards in the section, and therefore, with time. The confinement of the glacial stream after it exited the ice sheet was thus released with time, as the ice walls melted and allowed the stream to migrate more freely.

High angle reverse faults in associated deposits indicate the presence of buried ice (McDonald & Shilts, 1975) which, upon melting, triggered a resettling of the sediment to accommodate the open space left by the melted blocks. Melting of sustaining ice walls would also initiate slumping to

maintain a stable slope. Normal faults would be produced during slumping along esker margins.

Till at the base of an esker ridge implies that the esker forming stream was not capable of eroding it entirely. If it had, then the esker should rest on bedrock. It is improbable that a meltwater stream capable of transporting large boulders would not have been able to erode till. Since the fine mix unit, however, is the most common near the base of eskers, it may be that the meltwater stream is not as competent early on as it is later, likely when supraglacial meltwaters have contributed to the basal system. The esker-forming tunnel could also be assumed to have an englacial position, which is unlikely, as the discussion on meltwater in glaciers pointed out. The only place where till was observed under an esker ridge is at Huguette Lake, west of Labrador City and at a location not directly related to any of the large esker systems under study. On air photographs, that esker appears small, although it has extensive associated deposits in the form of flat pads which appear to be graded to a level controlled by a low, former outlet of a glacial lake, through the modern watershed in south-western Labrador. None of the exposures, however, reached bedrock, or even the base of the esker, so it cannot be assessed whether the Huguette Lake example is typical or an exception.

The presence of till under associated deposits is more easily explained, as it probably indicates that these were deposited on top of melting ice, after exiting the esker tunnel. The ice acted as a protective layer over the till, and meltout till could still be deposited as the ice melted, covered with associated deposits. The glacial stream had likely lost most of its erosive power.

In a few instances, in Gabbro and Ossokmanuan eskers, a till-like unit comprising subangular clasts in a clayey-silty matrix, was observed near the base of sections as irregular lenses. Their presence may indicate collapse of part of the ice roof and depcsition of pockets of till, or, alternatively, transport of frozen till blocks within the fluvioglacial system which essentially acted as large clasts. Till blocks may be more common than recognized, but their size (<1 m across) and poor exposure through most esker systems did not allow mapping their full extent.

ESKER LITHOLOGIC COMPOSITION

Construction of lithologic curves

To compare lithologic data from all eskers, lithologic curves at the same scale (1:500,000) and datum were constructed (Fig. 25). The datum refers to a location along the esker ridge, either the up-esker contact of the esker with the indicator in bedrock («entry» point, A on Fig. 25), or the down-esker contact with the indicator in bedrock («exit» point, B on Fig. 25) The second calibration is necessary because not all indicator bedrock are the same width. The intersections between eskers and indicator bedrock are the only points which can be unequivocally identified from maps for all rock types. If an indicator bedrock type is located up-esker from the head of the esker, then the zero datum is estimated by projecting a line in the opposite direction to regional ice flow from the head of the esker to the indicator bedrock (Fig. 25B). If an indicator bedrock is not crossed by the esker, then the zero datum is estimated by projecting a line along ice flow direction from the up-ice bedrock contact to the esker (Fig. 25C). For till, entry and exit points are the up-ice and down-ice contacts respectively, on the esker, of an indicator source.

«Entry curves» show the response to the addition of an indicator rock to the composition of esker sediments. The rock type, and more specifically its erodibility should control the strength and rapidity of the response, as referenced from the initial crossing of the esker to the indicator source. The width of the outcrop, however, should control the length of esker over which the percentage of indicator debris stays high.

Zero datum for «exit curves» is located at the down-esker contact with the bedrock source of indicator debris. Exit curves show the decrease in indicator values when the bedrock source is shut off. The portion of esker exit curves outside the till dispersal train show decreases in indicator lithology when all sources, bedrock and till, are shut off. Ideally, zero datum for esker exit curves should be located where the esker exits the till dispersal train of the indicator lithology under study. Eskers, however, usually run subparallel to till dispersal trains, and eskers crossing an indicator source are rarely outside its glacial dispersal train, and are thus constantly «fed» by adjacent till. Only four

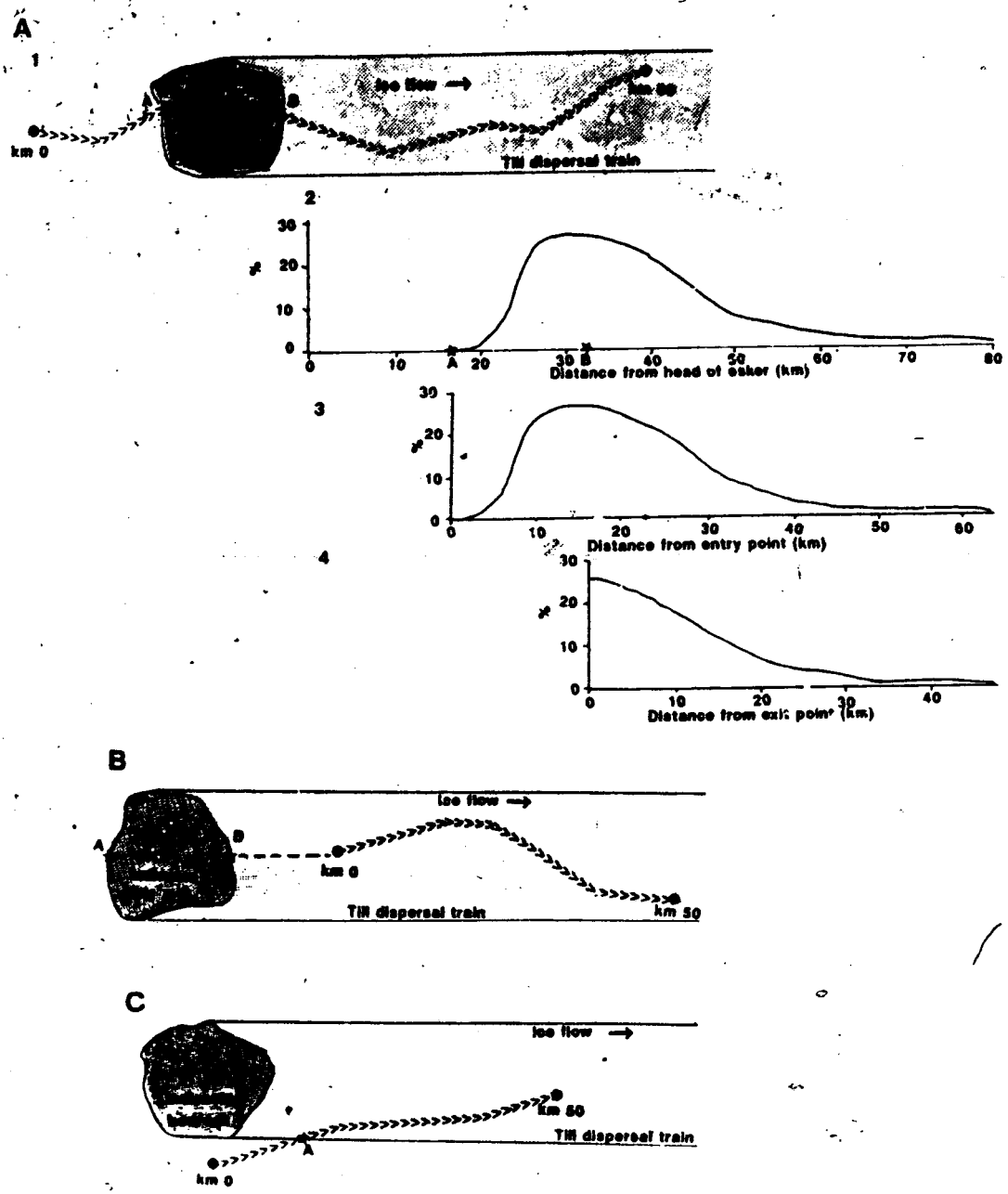


Figure 25. Sketch diagrams of lithologic curve calibrations. The head of the eskers (km 0), their end (A: km 80, B and C: km 50), as well as entry (A) and exit (B) points are identified. A) When esker path crosses indicator bedrock 1: Esker path through indicator bedrock and till dispersal train. 2: Lithologic curve along esker. Distances are calculated along the ridge line. Entry (A) and exit (B) points are identified. 3: Entry curve. This recalibration allows to visualize how a lithologic profile changes after input of an indicator rock. 4: Exit curve. This curve shows how the concentration of an indicator rock changes outside the outcrop area, an «unequivocal» point of exit, but still within the till dispersal train. B) When esker path lies within indicator dispersal train, but does not cross indicator bedrock. C) When esker path crosses indicator dispersal train.

esker curves outside the till dispersal train can be constructed from the data in this study, three of which are related to the Strange Lake peralkaline granite (SLPG) (cobble, pebble, and sand sizes), and the other to the quartz monzonite surrounding the SLPG.

Portions of exit curves «some distance» down-esker from the exit point can be called «distal curves». Distal curves have indicator lithology values <8-10 wt%, and the shape of the curve is smooth. Distal curves serve to evaluate the level of an indicator lithology at which there are no significant changes in the lithologic composition of an esker. Distal curves can be located at any distance from the bedrock source, but are found, in the case of esker distal curves, within the till dispersal train for the same indicator lithology.

The lithologic composition of esker ridges has been investigated for various indicator lithologies, size fractions, and individual ridges (Table 5, Appendix VII). Counting variability has been assessed by duplicate counts of randomly selected samples, is <1% for sand counts, <3 wt% for pebble counts and <7.5% for cobbles counts (Table 6). To ease the interpretation of the data, moving averages of five samples (average value of five samples plotted at the averaged distance, or location, for the same five samples) for selected curves have been performed. The raw and average curves were compared visually to determine whether moving averages eliminated noise interpreted to be random (if the general shape of the curves stayed the same after averaging) without completely obliterating the information given by the curves. It was found that for longitudinal curves, the moving average curves could be used because the magnitude of the response in esker composition is greater than 8-10 wt%, and persists for «some» distance down-esker. However, to investigate the details of the effect on lithologic composition of the junction between a tributary and a trunk esker, no smoothing was employed as the moving average curve would have eliminated any response which may have been present (Fig. 26, point A).

Sample density varies along an esker (Fig. 26), and between eskers. Note, for example, that the scale of investigation at junctions changed to determine the effect, if any, of tributaries on trunk esker composition. The sample spacing (density) was changed to reflect the apparent size of the

	Lithologic types													
	Quartzite		Arkose		Iron formation		Volcanic		Slate		Strange Lake peralkaline granite			Quartz-monzonite
	C	P	C	P	C	P	C	P	C	P	C	P	S	P
Central Labrador														
Till		e		e		e		E,e		e				
Gabbro	e	e	e	e	e	e	E,e	E,e	e	e				
Ossokmanuan		e		e		e		E,e		e				
Western Labrador														
Till						E,e				E,e				
Shabogamo						E,e				E,e				
De Mille						E,e				E,e				
Moose Head						e				E				
Ashuanipi						e				E				
Northern Labrador														
Till		e										E,e	E,e	E,e
Lac Brisson	e	e									E,e	E,e	E,e	E,e

Table 5. Lithologic data used in the study of transport of debris along an esker. C: cobble; P: pebble; S: sand; E: entry curve; e: exit curve.

Sector	Indicator lithology	Cobbles count %	Pebbles weight %	Sand count %
		n=12	n=15	
Central	Sims quartzite	0.89	0.76	
	Arkose	3.26	1.15	
	Iron formation	0.90	0.39	
	Volcanic rocks	4.23	1.06	
	Slate	7.55	2.35	
			n=22	
Western	Iron formation		1.13	
	Trough slate		2.70	
			n=53	n=37
Northern	Quartz-monzonite		2.86	
	Quartzite		1.31	
	SLPG		2.51	0.65

Table 6. Estimates of the counting variability for each indicator lithologies and for each size fractions reported. The estimates represent ± the 99% confidence interval, for «n» duplicate counts, as estimated by the comparison of paired samples (Snedecor and Cochrane, 1980, pp. 91-95). Note that the least reproducible results are for slate and volcanic cobbles, which were found in the field to be difficult to distinguish in the absence of particular characteristics such as bedding (slate) or albitization (volcanic rocks).

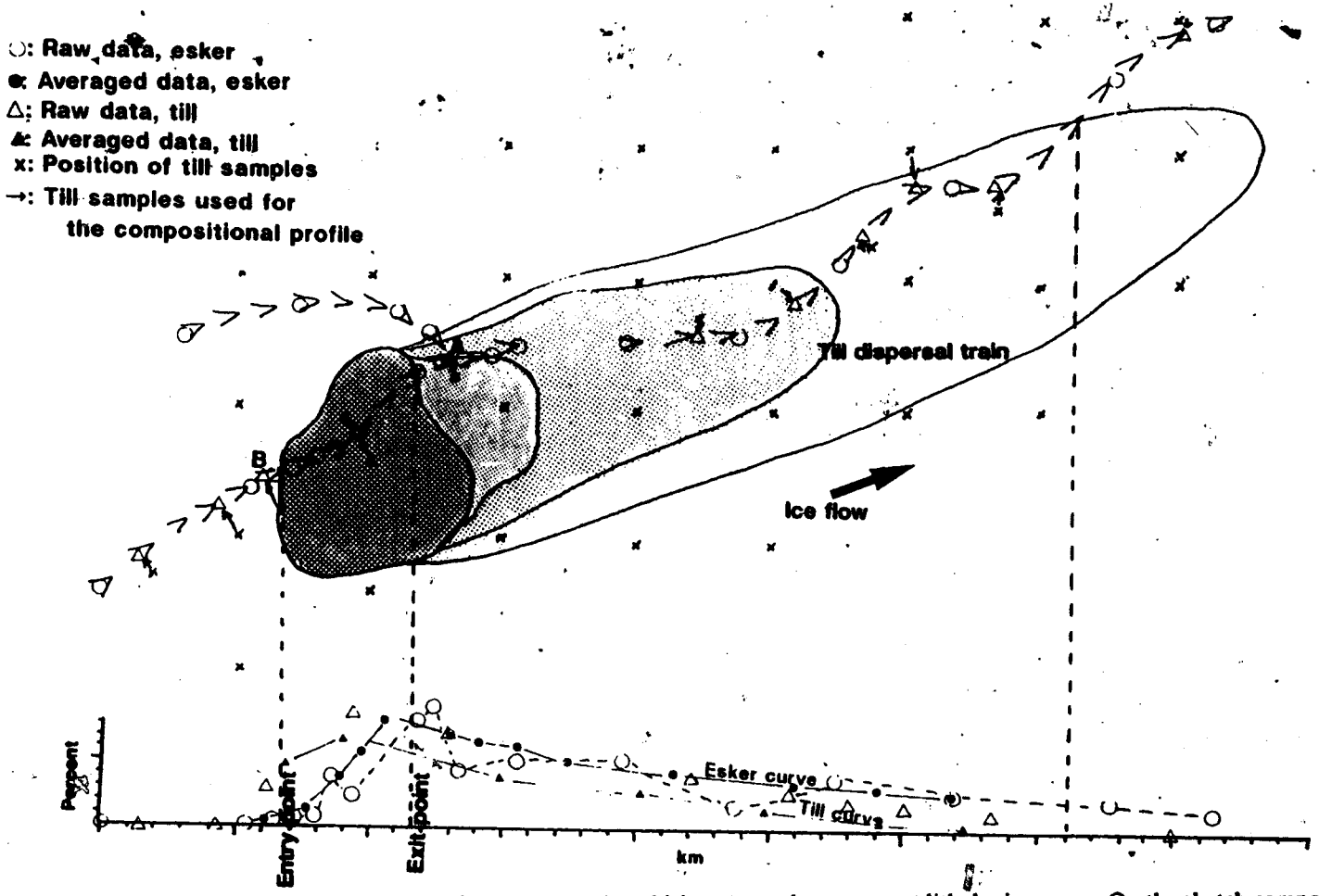


Figure 26. Sketch diagram of sample locations for those samples which were used to construct lithologic curves. On the sketch compositional diagram, the position of the raw data is plotted to show how the data are modified by the 5-samples moving average. A) At a junction, averaging may eliminate any indications of the influence of a tributary on the trunk composition (solid curve), while using the original data (dashed curve) it is apparent that the composition of the trunk esker is diluted by input from the tributary. B) Example (drawn from Lac Brisson area) of how a till sample can have indicator pebbles, even if it plots before the zero datum.

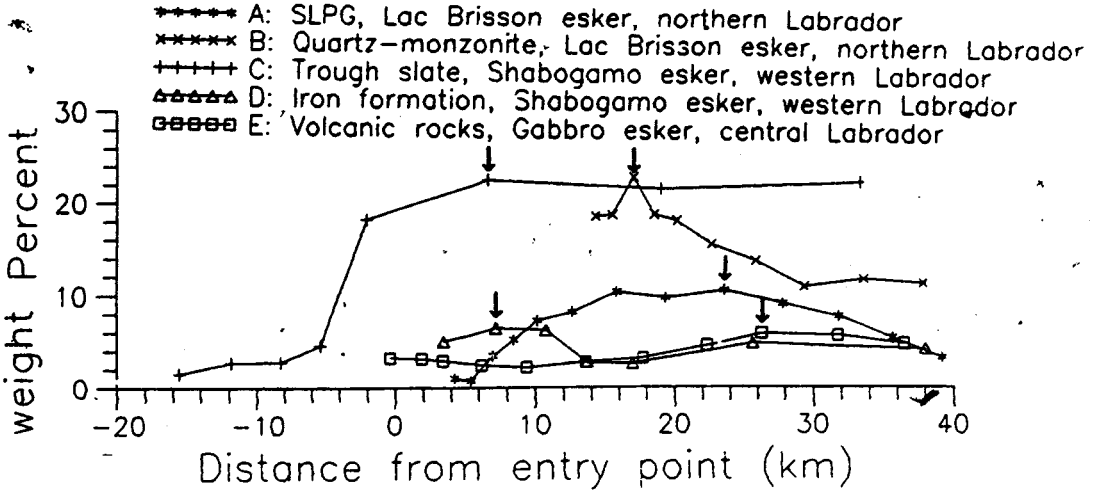
feature. Smoothing over a fixed distance (eg. 5 km) regardless of sample density, however, would not have been appropriate. Smoothing over 5 km would have meant using one sample along some portions of an esker, and using up to 10 samples along other segments. In order to treat all eskers similarly, a moving average of 5 samples appeared the best treatment, and the following discussion refers to the smoothed curves.

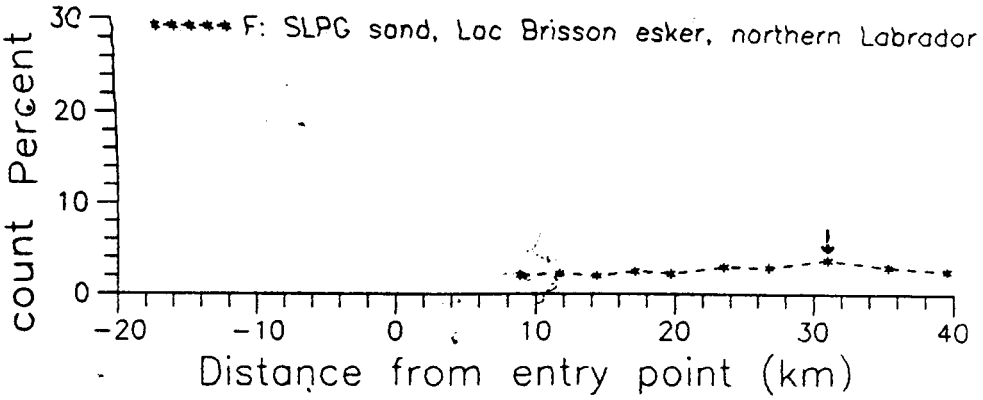
The samples used to construct till entry curves were located within 1.5 km on either side of the esker, and plotted at the kilometre mark perpendicular (with respect to esker path) to their position. Some till entry curves show that there is indicator debris before the 0 km mark, which can be explained by one of three reasons. Firstly, an averaged data point may be plotted before the 0 km mark on the lithologic curve (average distance of 5 samples), as it reflects some samples which are located on indicator bedrock, and which, therefore, have indicator debris. Secondly, esker paths and bedrock contacts are not perpendicular, and some till samples were located on indicator bedrock, while the equivalent kilometre mark on the esker was not (Fig. 26, point B). Thirdly, pre-late glacial dispersal, in a different direction than late glacial flow, may have brought indicator debris to a location which appears to be up-glacier from the bedrock source.

For esker entry curves, the presence of indicator pebbles before the 0 km mark may be due to the effect of the rolling average or to pre-late glacial dispersal, as for till, but also to input of debris into the esker tunnel by ice creep, especially where esker paths run sub-parallel to bedrock contacts before actually crossing the contact. These examples are minor, however, and dot not seem to obscure the interpretation of till dispersal trains and esker lithologic curves.

Till entry curves

In till, there were not enough data to derive entry curves, in till, for the cobble fraction. For the pebble fraction, 5 entry curves are constructed (curves A, B, C, D, and E, Fig. 27). The pebble lithologic curves show maximum abundance of indicator lithologies 6.5-26.25 km from the up-esker bedrock-esker intersection (10.48 wt% at 23.55 km, curve A; 22.82 wt% at 17.00 km, curve B; 22.61 wt% at 6.60 km, curve C; 6.48 wt% at 9.70 km, curve D; and 5.85 wt% at 26.25 km, curve E, Fig. 27).





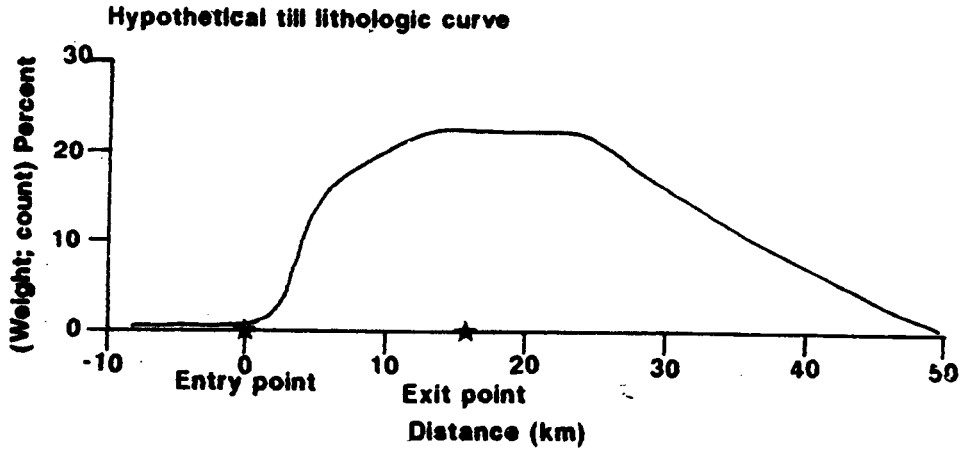


Figure 27. Till lithologic entry curves. The arrows point to the maximum value on each curve. Pebble data unless otherwise stated. The hypothetical till lithologic curve given here is a qualitative composite of the data presented in the *«Till entry curves»* section.

The till entry curve comprises three segments before peak abundances (curves A and C, Fig. 27). The first segment has low (2-3 wt%) quantities of indicator lithology, and may reflect low percentages before, and for a short distance afterwards, the contact. The second segment shows an abrupt increase (about 5 wt%/km) in percentages indicates the input of indicator lithology to the system, and is typical of till dispersal trains (Shilts, 1982; Clark, 1987) near the source. The third segment is a gentler rise (about 0.5 wt%/km) to peak abundance, which is not typical of till dispersal trains, but may be an artifact of the moving average, or could also reflect the fact that the compositional profile may not be oriented in the path of maximum compositional changes. A fourth segment, after peak abundances, shows a varying rate of decrease in indicator abundances.

The sand entry curve shows peak abundance at 31.05 km (3.79%, curve F, Fig. 27). SLPG sand, however, is only those sand grains which luminesced red under cathodoluminescence, and other sand grains from SLPG were not recognized, hence not counted. For this reason, the SLPG sand curve is to be interpreted with caution. Since there are no other sand entry curves in till, it cannot be categorized further.

Surface till interpreted to be meltout till was sampled in this study. This may explain why peak abundances of indicator pebbles - and sand - are located so far from the bedrock source. Sampling lodgment till should have given entry curves with peak abundances close to the beginning of the source, with an abrupt rise to peak abundances (Shilts, 1982; Clark, 1987). Meltout till dispersal commonly has lower percentages of indicator debris than lodgment till, but indicator debris is transported farther in meltout till than in lodgement till (Batterson, 1989).

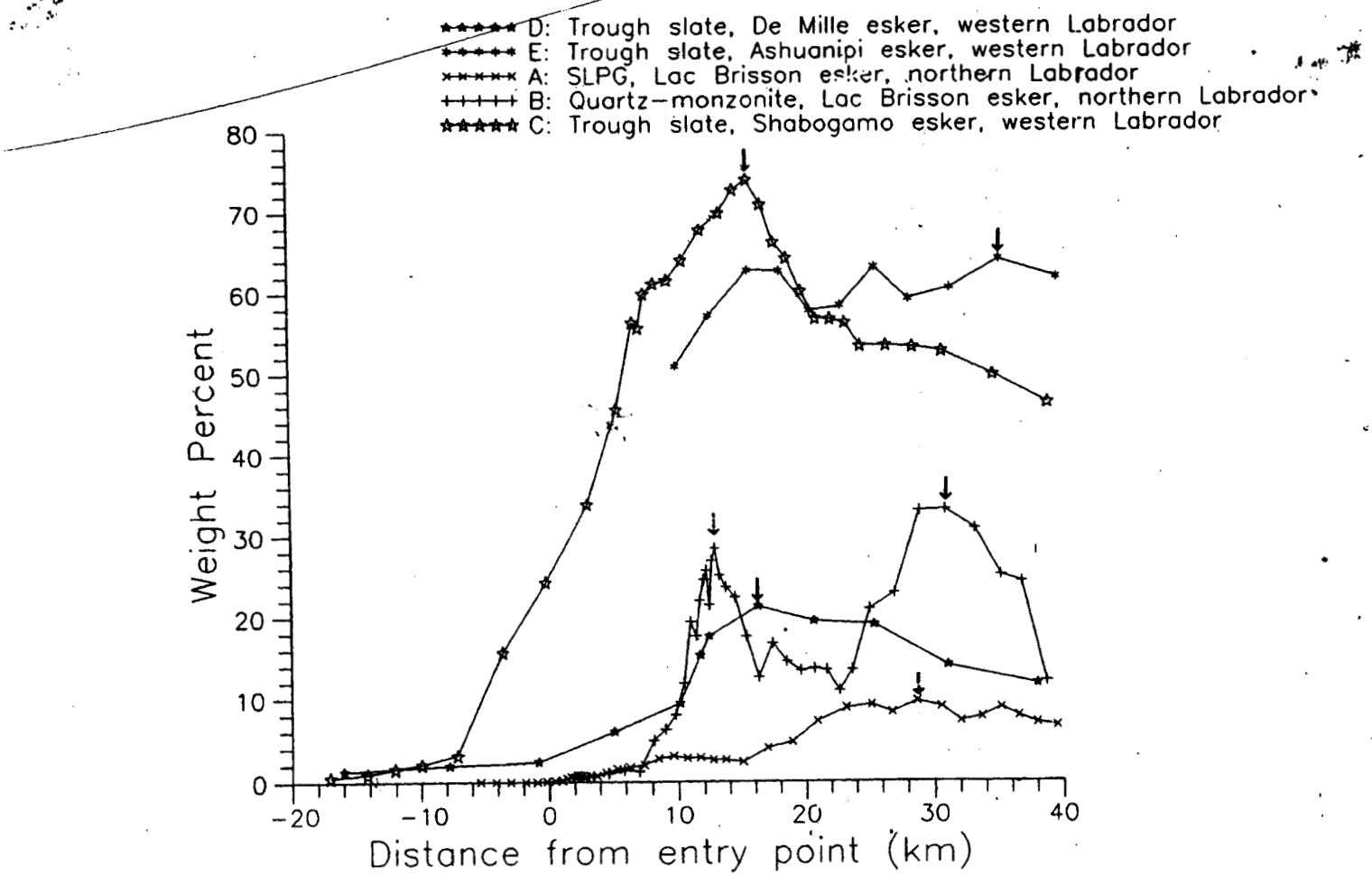
Some differences between lithologic curves can be related to differences in rock type and extent of outcrop area. Indicator lithologies with low erodibility and narrow, ribbon-shape outcrop area (iron formation, curve D, and volcanic rocks, curve E, Fig. 27) have low abundances (<7 wt%). Indicator lithologies with high erodibility and large outcrop area (quartz-monzonite, curve B, and slate, curve C, Fig. 27) have high abundances (up to 22.82 wt%). Strange Lake peralkaline granite (SLPG; curve A, Fig. 27) has a small outcrop area, but is more erodible than volcanic rocks or iron

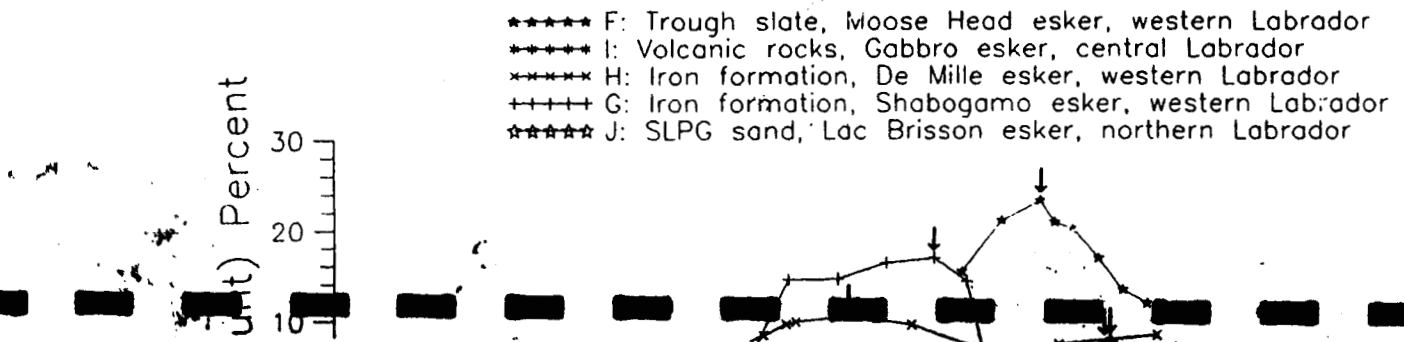
formation, and has intermediate abundances (up to 10.48 wt%).

Esker entry curves

In eskers, one sand entry curve, two cobble entry curves and 10 pebble entry curves were constructed (Fig. 28). All esker entry curves start with low percentages of indicator lithologies (<2 wt%) for about 6 km from the zero datum, followed by a sharp increase to values >12 wt% within about 6 more km. The percentages of indicator lithology then either rapidly decrease (2.5 wt% per km) to near background values, or stay at about the same levels for varying distances (5-10 km). Maximum values of indicator lithology are between 7 and 75 (wt) %, and should be noted to occur between 15 and 35 km of the entry point. The abruptness of the rise to maximum value, as well as the distance over which high levels of indicator lithology are found appear dependent on the rock type and size of indicator lithology outcrop, as well as position within the glacial dispersal train. For instance, the concentrations of Trough slate pebbles in western Labrador, which is a soft, easily erodible lithology, increase rapidly to high concentrations (maximum value of 74.03 wt%) in Shabogamo esker (curve C, Fig. 28). For De Mille esker (curves D and F, Fig. 28) the concentrations are much lower (maximum value of 21.37 wt%), even though the rise is as abrupt as for Shabogamo esker. This pattern can be explained by the length of esker found on Trough slate bedrock, which is about 12 km for Shabogamo esker, while De Mille esker does not actually run over Trough slate bedrock, but is located in its till dispersal train. On the other hand, the concentrations of iron formation, a hard lithology, are equivalent for Shabogamo esker (maximum value 16.7 wt%, curve G, Fig. 28) and De Mille esker (maximum value 10.34 wt%, curve H, Fig. 28), both running over iron formation bedrock for equivalent distances. The concentrations of iron formation pebbles are much lower, however, than Trough slate pebbles, which are a much more erodible lithology.

The location of the esker with respect to the till dispersal train may be crucial in the fluctuations of indicator lithology levels. Accordingly, eskers which are located well inside a till dispersal train (eg. Shabogamo esker in Trough slate dispersal train, curve C, Fig. 28) show a regular increase and decrease in indicator levels, while those located at the edge of a till dispersal train (eg.


D: Trough slate, De Mille esker, western Labrador
E: Trough slate, Ashuanipi esker, western Labrador
A: SLPG, Lac Brisson esker, northern Labrador
B: Quartz–monzonite, Lac Brisson esker, northern Labrador
C: Trough slate, Shabogamo esker, western Labrador
Weight Percent
80
70
60
50
40
30
20
10
0
−20
−10
0
10
20
30
40
Distance from entry point (km)


F: Trough slate, Moose Head esker, western Labrador
I: Volcanic rocks, Gabbro esker, central Labrador
H: Iron formation, De Mille esker, western Labrador
G: Iron formation, Shabogamo esker, western Labrador
J: SLPG sand, Lac Brisson esker, northern Labrador
30
20
10

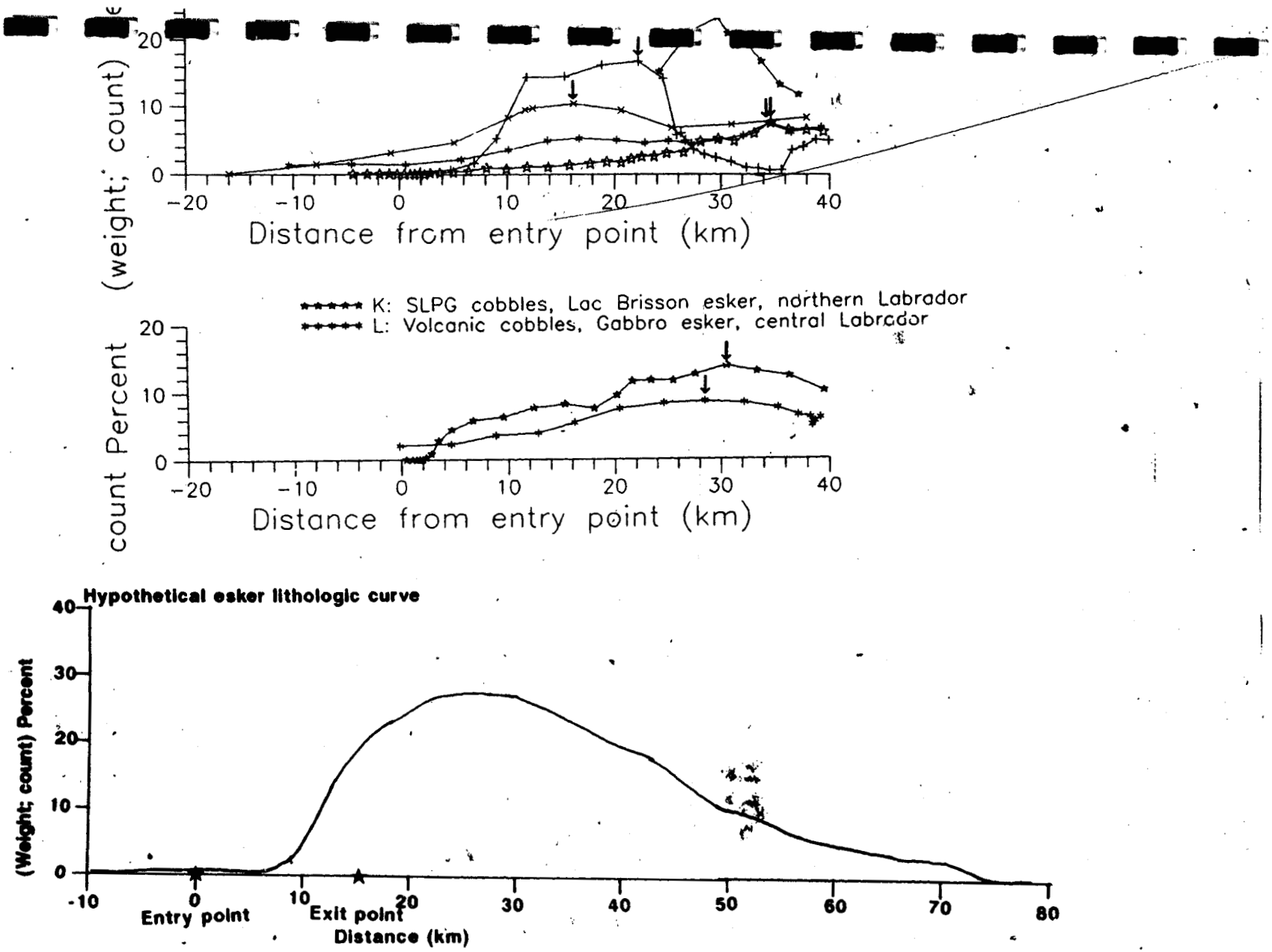


Figure 28. Esker lithologic entry curves. The arrows point to the maximum value on each curve. Pebble data unless otherwise stated. The hypothetical esker lithologic curve given here is a qualitative composite of the data presented in the «*Esker entry curves*» section.

Lac Brisson esker, quartz monzonite pebbles, curve B, Fig. 29) show variations which can only be explained by input of other rocks in the drainage basin of the esker or differences in input of indicator debris.

Quartz monzonite pebble concentrations (Fig. 29), for example, increase abruptly to a near maximum value of 28.53 wt% (broken arrow, curve B, Fig. 29), then decrease just as abruptly, stay «low» (~ 14 wt%) over a distance of 10 km. Since no other source of quartz monzonite occurs west of SLPG (Fig. 4), and because the levels of SLPG pebbles are not enough (< 3 wt% along this reach of the esker) to dilute the levels of quartz monzonite, there has to be input of other rocks. Lac Brisson esker is located at the northern edge of the till dispersal train for quartz monzonite, and it is likely that input of gneisses to the esker are responsible for the decrease in quartz monzonite noted. Further along, the esker path is located more «inside» the quartz monzonite till dispersal train, and the levels of quartz monzonite rise to the maximum value of 33.29 wt% (curve B, Fig. 29).

Till exit curves

In till, pebble exit curves could have been constructed for 10 indicator lithologies. The levels of indicator lithology pebbles, however, are less than 8 wt% for six of those pebble exit curves, and do not exhibit particular features. Those six exit curves appear more analogous to distal curves than to exit curves.

As for the other four pebble exit curves (Fig. 30), they show a gently sloping plateau, with an overall decrease of <0.3 wt% per km for 30-40 km after the exit point, followed by a more «abrupt» decrease of 0.6 wt% per km (curves A, B, C, and D, Fig. 30). The length over which the moderate decrease takes place appears to be dependant on the size of the source area, such that smaller bedrock outcrops produce shorter plateaus, while larger outcrops make longer plateaus. Curve A (Fig. 30) is associated with SLPG which is a very small (<5 km) source. The concentrations of SLPG pebbles therefore decreases much sooner (~ 20 km from the exit point) than for other rock types. The sand exit curve (E, Fig. 30) is essentially a background curve, but is kept here because the location of the point of exit from the till dispersal train can be plotted, at km 42.

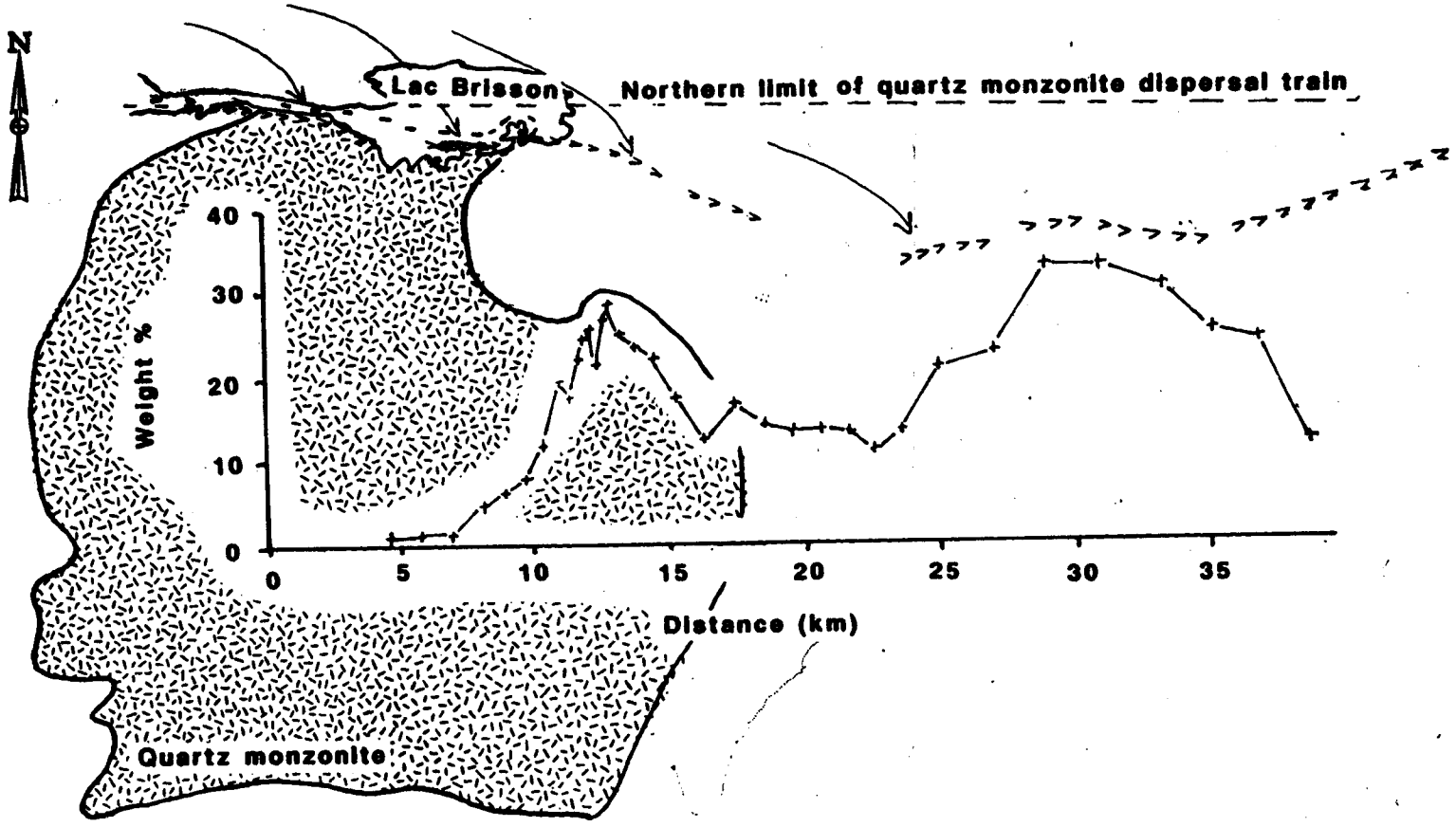


Figure 29. Details of the dispersal patterns in till and esker of quartz monzonite pebbles. The location of Lac Brisson esker near the northern edge of the till dispersal train appears to influence the fluctuations of quartz monzonite pebbles, such that input, by ice creep, of non-indicator pebbles located in the drainage basin of the esker dilute the levels of indicator quartz monzonite.

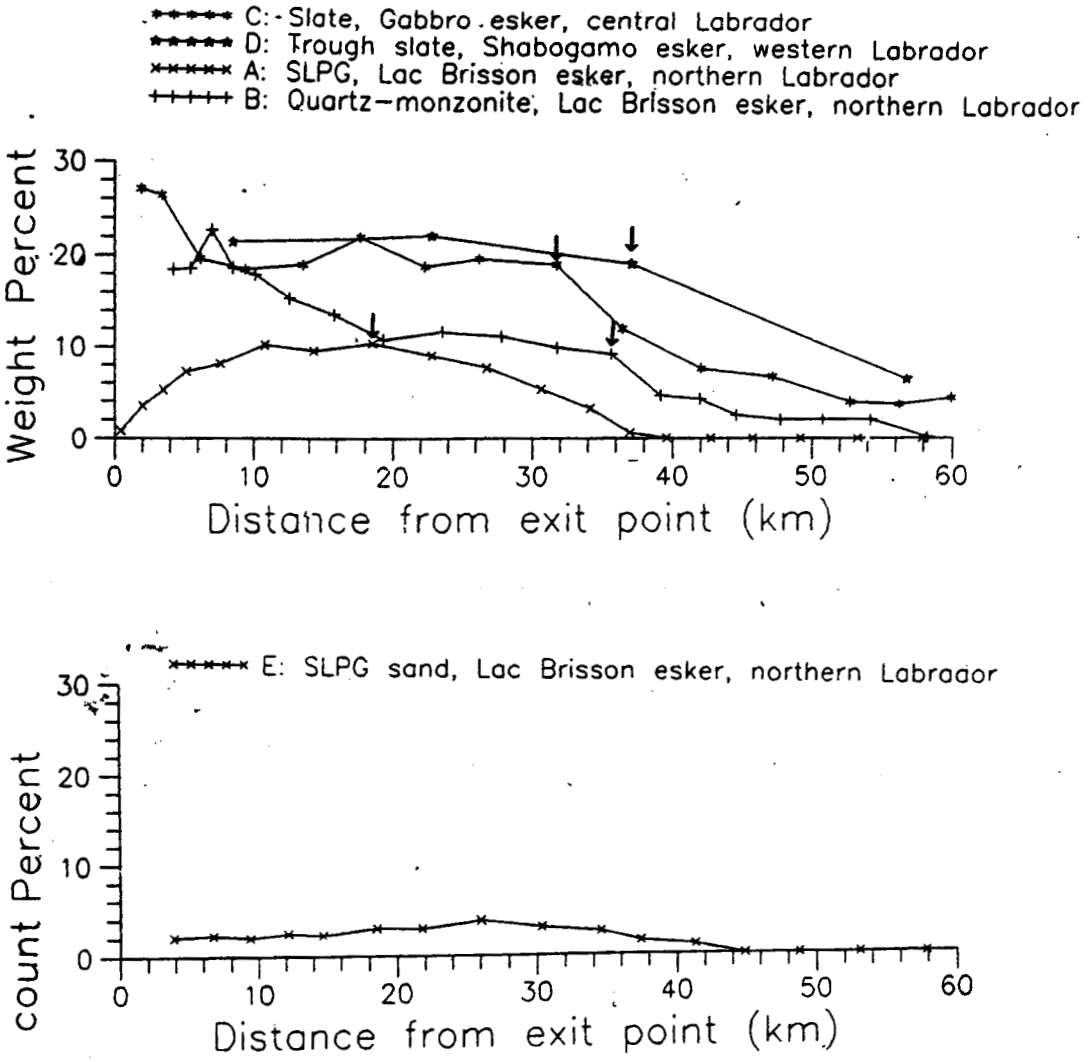


Figure 30. Till lithologic exit curves. The arrows indicate the inflection points where the concentration of indicator clasts decreases markedly.

The shape of till exit curves do not show an exponential decrease away from the source, as has been proposed for the shape of an idealized till dispersal train (Shilts, 1976), and does not show an immediate decrease after leaving the indicator bedrock. In this study, however, compositional profiles may not always be in the axis of maximum concentration changes, which may explain the differences with the idealized curves. The surface till sampled is interpreted to be meltout till, and as a result, indicator debris appears to have been transported farther down ice than it would have in lodgement till.

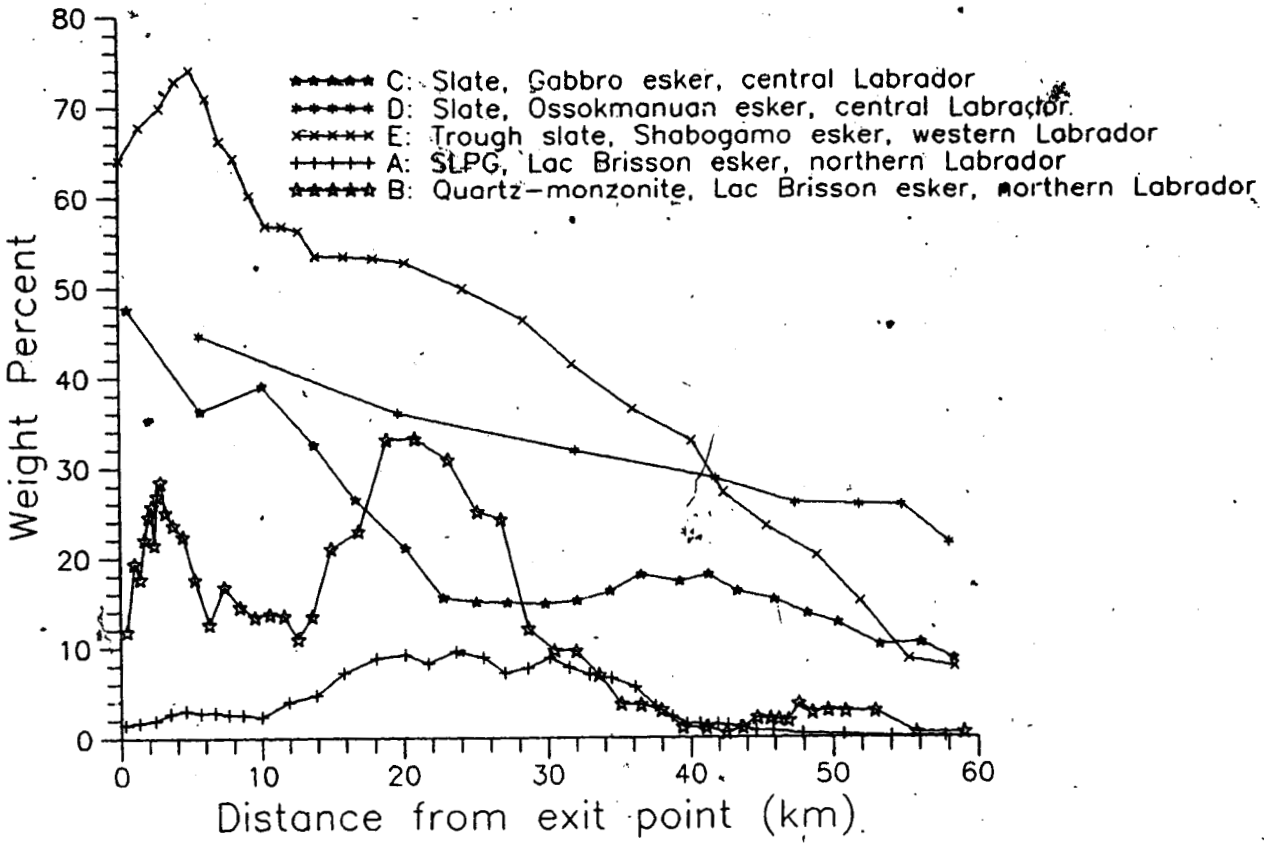
Esker exit curves

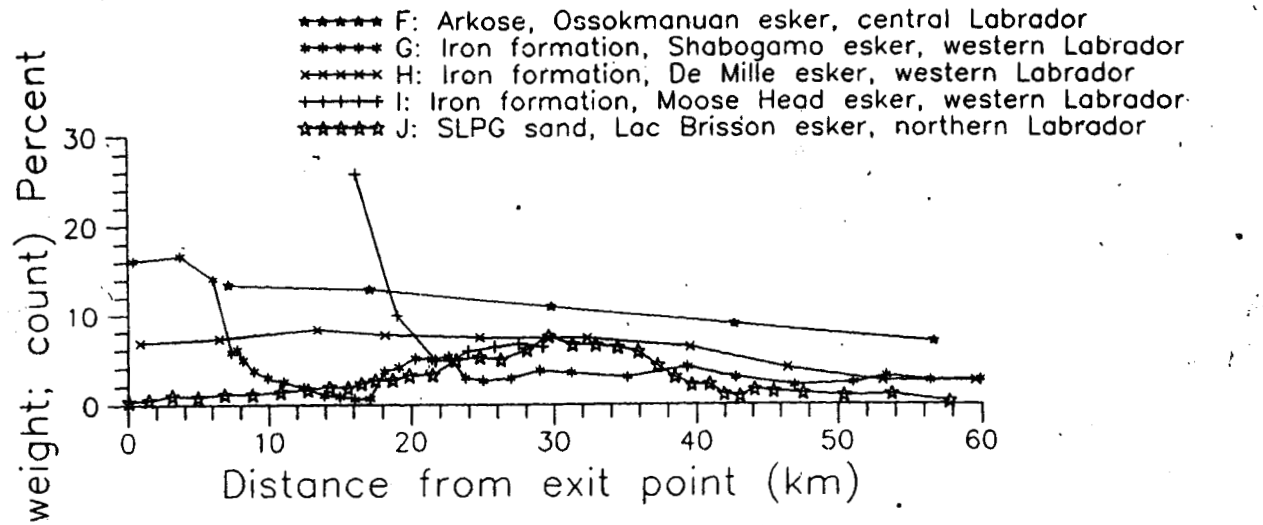
In eskers, 19 pebble exit curves, 7 cobble exit curves, and 1 sand exit curve could be constructed. Similar to till, however, 12 of these curves have indicator lithology values < 8 wt%, and show no particular characteristic.

An abrupt decrease can be noted (1-3 wt% per km) for pebbles and cobbles from the maximum or plateau value to the distal area of the curves (Fig. 31). Because the maximum indicator lithology value is located 15 to 35 km from the entry point, and because indicator bedrock outcrop areas differ from rock type to rock type, the location of the beginning of the steep decrease in indicator lithology varies substantially (6-36 km) from the exit point.

Because most eskers remain within the till dispersal train of the indicator lithology it is likely that there is input of indicator debris along the length of the esker. Thus, concentrations of indicator lithology pebbles reflect both glacial and fluvioglacial transport. Where the esker leaves the dispersal train the curves reflect changes that result from fluvioglacial transport, and associated processes. In practice, the significance of esker curves outside the till dispersal train is that if a point can be determined along the esker path where an indicator lithology can no longer be incorporated, then the length of esker beyond that point along which said indicator lithology is found, is a minimum value of the esker tunnel length. In this study, there are only four true exit curves, all located in northern Labrador (Fig. 32).

The path of Lac Brisson esker changes drastically northeast of Strange Lake, in order to cross


C: Slate, Gabbro esker, central Labrador
D: Slate, Ossokmanuan esker, central Labrador
E: Trough slate, Shabogamo esker, western Labrador
A: SLPG, Lac Brisson esker, northern Labrador
B: Quartz–monzonite, Lac Brisson esker, northern Labrador
Weight Percent
Distance from exit point (km)


F: Arkose, Ossokmanuan esker, central Labrador
G: Iron formation, Shabogamo esker, western Labrador
H: Iron formation, De Mille esker, western Labrador
I: Iron formation, Moose Head esker, western Labrador
J: SLPG sand, Lac Brisson esker, northern Labrador
(weight; count) Percent
Distance from exit point (km)

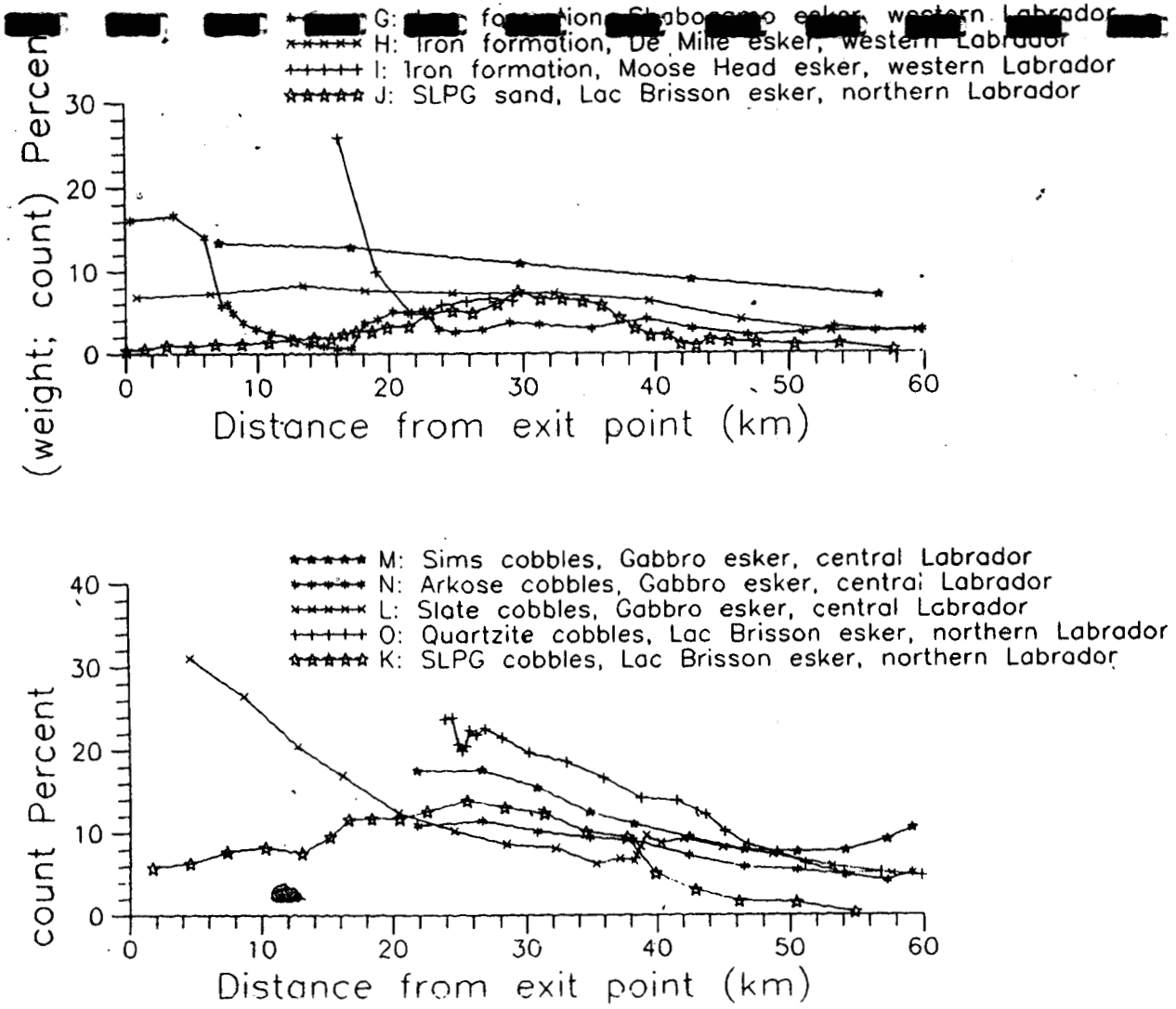


Figure 31. **Esker lithologic exit curves.**

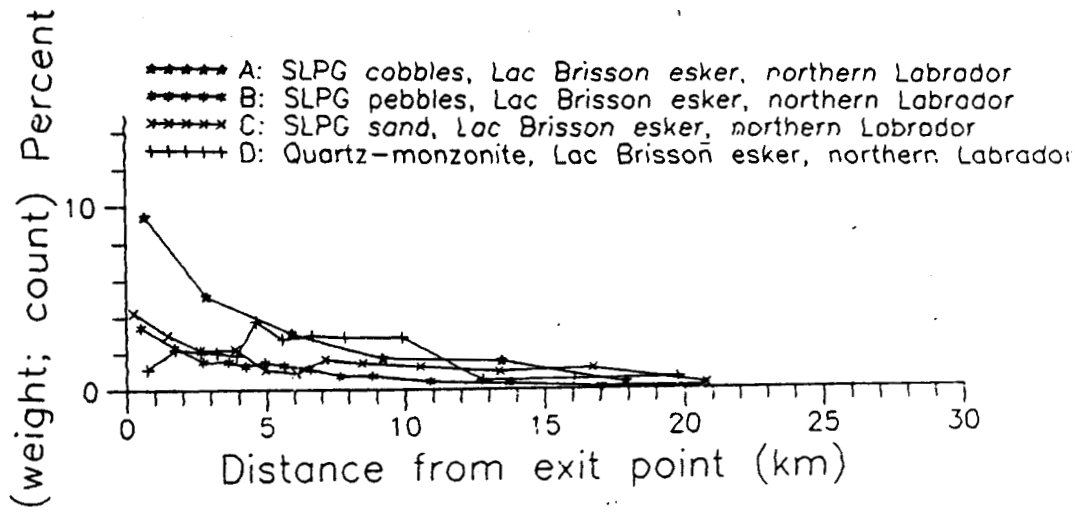


Figure 32. *Lithologic curves, Lac Brisson esker, outside the till dispersal train.*

some high topography at a low point. Because of this configuration, the path of Lac Brisson esker lies outside the glacial dispersal train of SLPG and quartz monzonite. The point of exit of the till dispersal train is difficult to locate precisely, because of lake cover and the lack of samples northwest of the esker. A theoretical point of exit is estimated by projecting a line along the last ice flow direction, from the northern margin, or projected margin, of SLPG and quartz monzonite. The exit points are at km 42 ± 1 for SLPG (km 0 being the proximal contact between the esker and SLPG), and km 53 ± 1 for the quartz monzonite (km 0 being the proximal contact between the esker and the quartz monzonite).

The shape of three of the four curves (A, B, and C, Fig. 32) indicates that there is a rapid decrease in indicator lithology once outside the till dispersal train, but some (< 2 (wt) %) can be found to the end of the esker, 21 km from the exit point. That some indicator lithology be found at the last plotted location is an artefact of the moving average. In fact, the last sampling sites do not have SLPG sand, pebble or cobble, but SLPG sand are found 25 km, SLPG pebbles are found 20 km and SLPG cobbles are found 7 km, down-esker from the approximate exit point. These data indicate that although the esker tunnel was functioning over a distance of about 25 km, cobbles were reduced in size during fluvioglacial transport. Transport of the pebble and sand sized indicator debris is greater, perhaps due to enrichment from the broken cobbles, or because smaller grains are not size-reduced, or both.

The exit curve for quartz monzonite pebbles (D, Fig. 32) is different than expected, because concentrations of quartz-monzonite pebbles do not start to decrease until 10 km from the estimated exit point. The exit point, however, was estimated by extrapolating from the northern margin of the quartz monzonite to the esker path in the direction of last regional ice flow. If the northern margin is located in Lac Brisson, the exit point would be located 6 km farther along the esker. From km 10 from the exit point, the quartz monzonite exit curve is similar to others, and also indicate transport to the end of the system, 20-25 km.

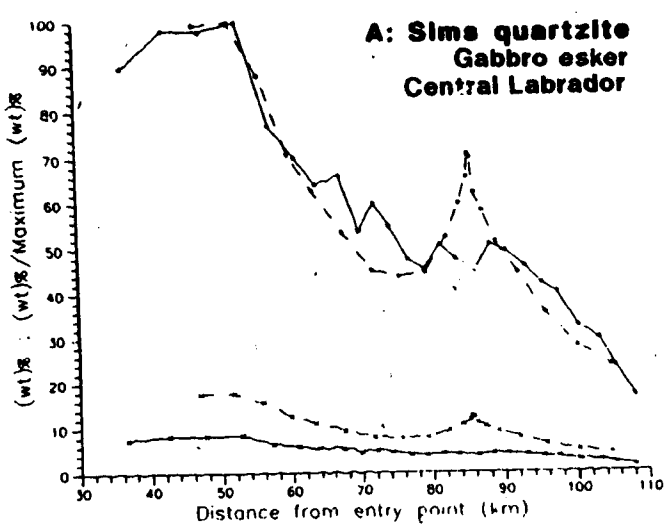
Size comparison, esker data

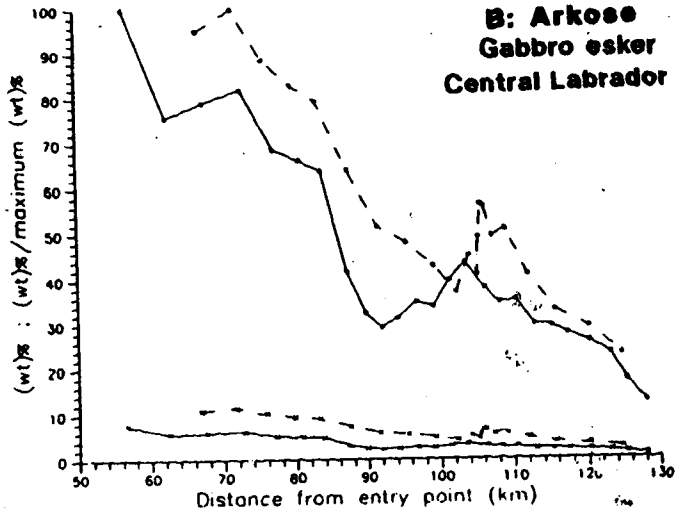
Cobble and pebble lithologic dispersal curves (averaged data) for the same lithology can be constructed for the dispersal of quartzite and SLPG in Lac Brisson esker, and Sims quartzite, arkose, volcanic rocks, iron formation, and slate in Gabbro esker. The abundance of iron formation in Gabbro esker, however, is too low (< 3 (wt)%) to compare the distributions of pebbles and cobbles.

Along the length of esker studied, quartzite, arkose, and SLPG (Fig. 33) cobbles are 2 to 5 times more abundant than pebbles; slate cobbles are ½ to ¼ as abundant as pebbles; and volcanic cobbles and pebbles are about equally abundant. Cobble and pebble distribution curves often mimic one another, and the standardized curves (percent/maximum percent vs distance (Fig. 33)) show that the rate of increase and, especially decrease, of each size fraction is the same. If cobbles had been mechanically broken during transport, it would be expected that their breakage would have produced pebble size fragments, and thus, that the rate of decrease of indicator pebbles would be less than that of cobbles. The similar rate of decrease of cobbles and pebbles therefore indicates resistance to mechanical breakage, or transport in a slurry, which effectively protected clasts from breakage.

Resistance to breakage is not important, since resistant rock types (eg. quartzite, volcanic rocks) as well as non-resistant rock types (especially slate) have the same rate of decrease down-esker from maximum abundance (50% loss in an average of 21 km, for both pebbles and cobbles). The similar rates of decrease of both pebbles and cobbles, and for different rock types, thus point to protection from breakage during transport of the clasts (in a protective slurry) in the fluvioglacial stream. The principal control on the curves is thus continued addition of other materials, and fluvioglacial processes of clast attrition have minimal effect.

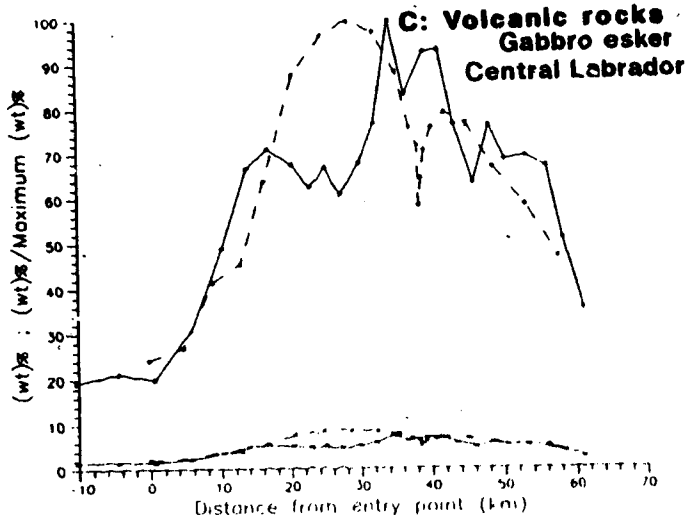
The case of SLPG is different from the other rock types. Lac Brisson esker leaves SLPG dispersal train, and is therefore not continuously fed by till. For this reason, SLPG abundances decrease by 50% in 8 (sand) to 13 km (pebble and cobble), probably reflecting absence of SLPG material input from till to the esker sediment past the exit point, rather than rapid comminution. The pebble curve also does not show enrichment from breakage of cobbles, another indicator that

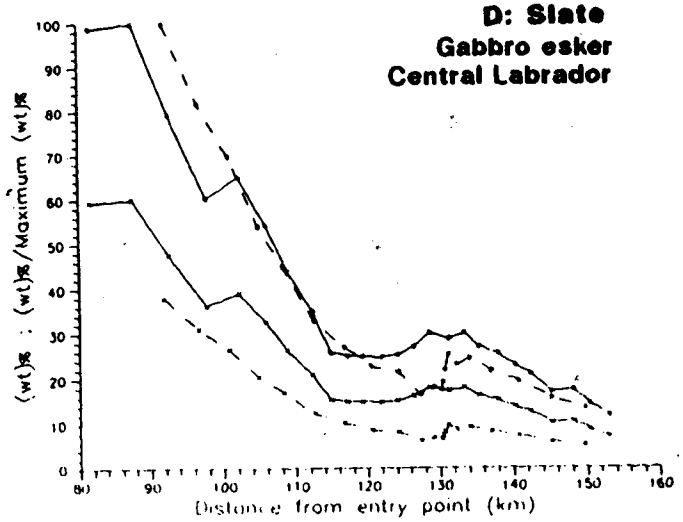




-----: cobbles

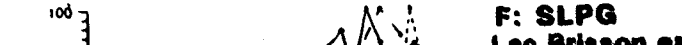
—— : pebbles





-----: cobbles —— : pebbles ····· : sand





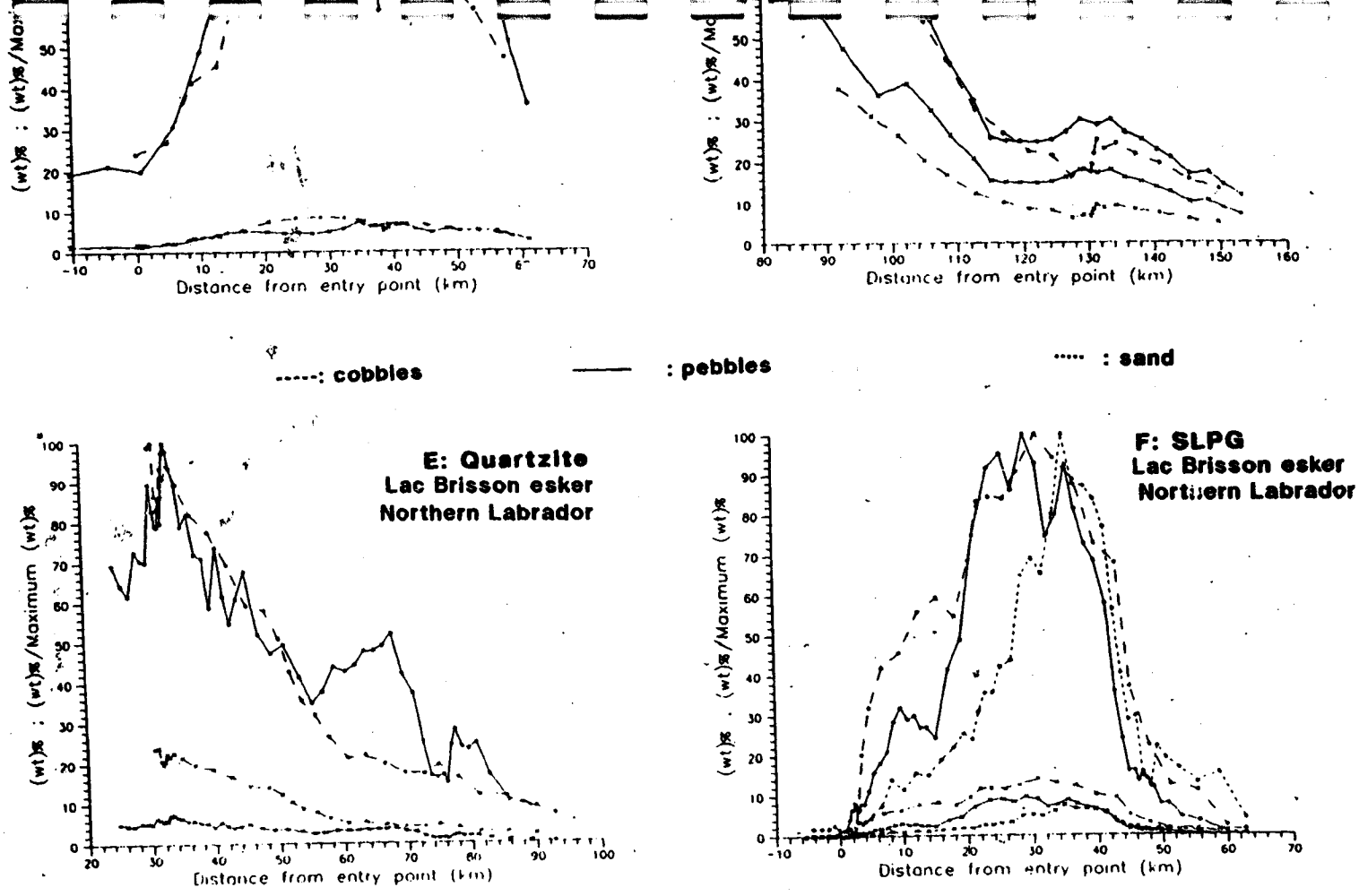


Figure 33. Lithologic curves (averaged data) according to size fractions. Direct plots (percentage vs distance, plotted as x) and standardized plots (percent/maximum percent vs distance, plotted as *) are shown. Distances are from the (projected) entry point, where the esker first crosses each bedrock type.

comminution is not very important.

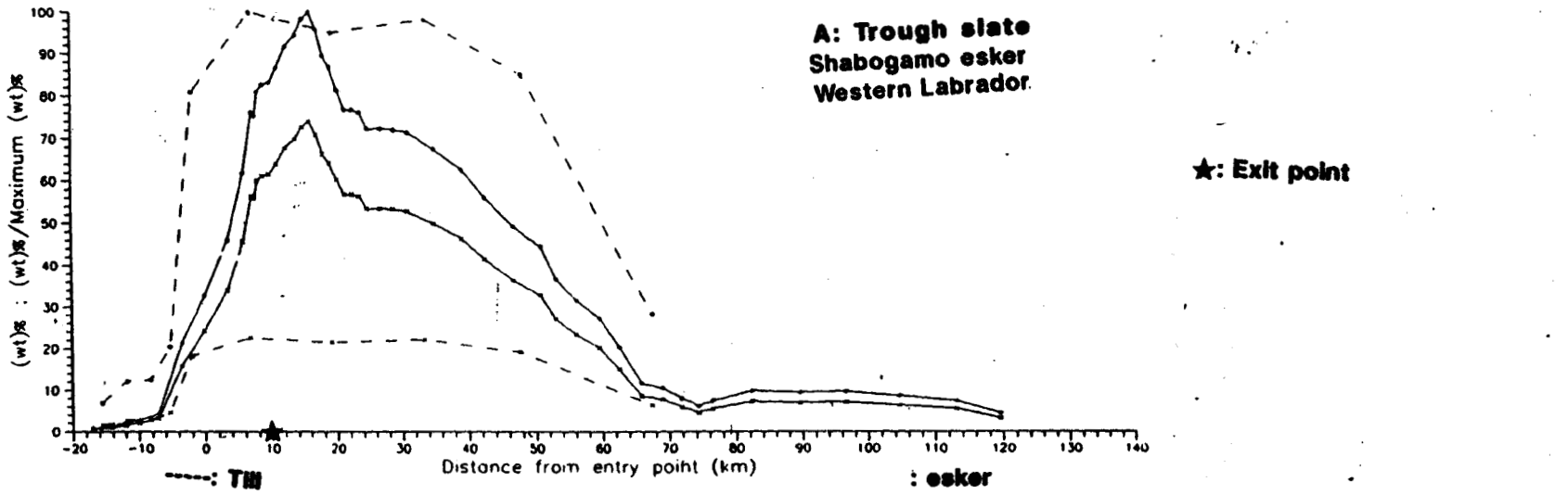
Transport of esker debris in an overloaded stream is indicated by the mixed units, in which clasts are found disseminated throughout the unit, rarely as clusters. Relative proportions of clast abundances within eskers are a direct reflection of their proportions within till. Thus, esker composition relates to glacial erosion of bedrock, rather than to fluvioglacial erosion of bedrock, and thus to the basal debris load in the ice.

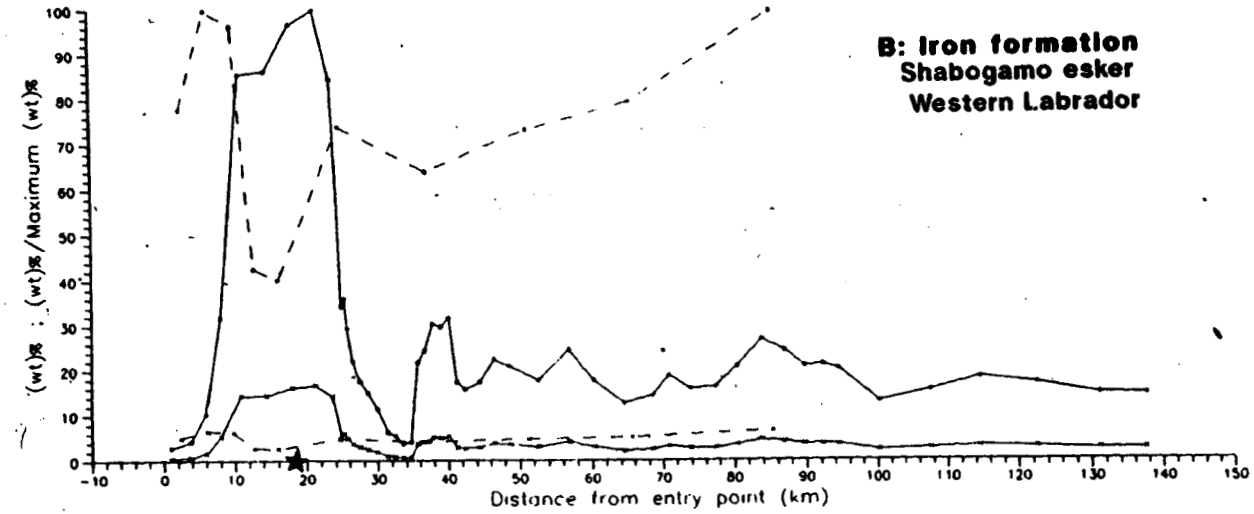
Material comparison

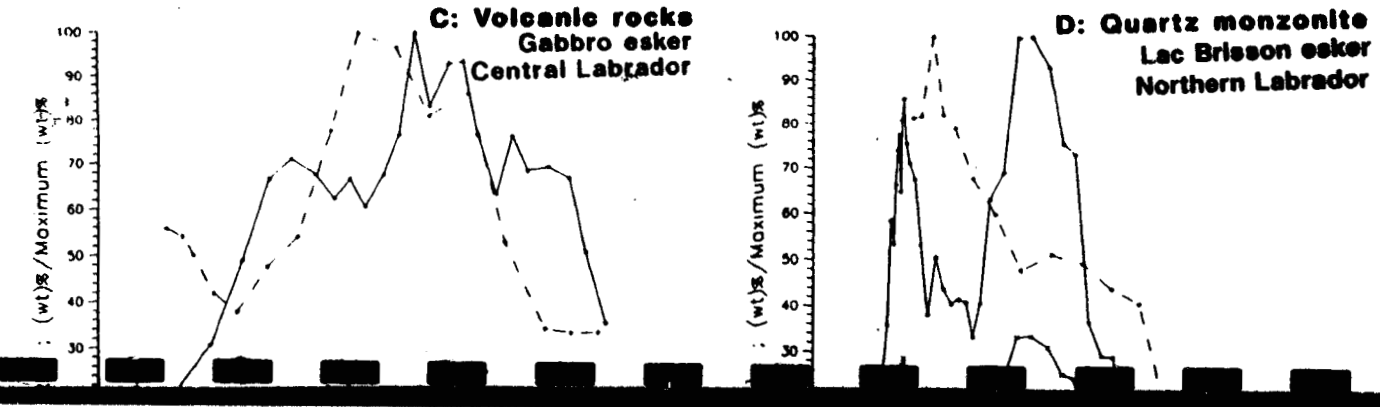
Lithologic curves (averaged data) for the same indicator in esker and till can be built for Sims quartzite, arkose, volcanic rocks, iron formation, and slate (Gabbro esker); slate and iron formation (Shabogamo esker); quartzite, quartz-monzonite, and SLPG pebbles and sand (Lac Brisson esker) (Fig. 34). Percentages of iron formation in Gabbro esker and adjacent till are too low (<3 wt%), however, to use in a comparison study. Because the entry curve is not available for quartzite of the Sims Formation and from northern Labrador, as well as for arkose and slate (Gabbro esker), those curves cannot be used in this section, because it is unclear how the till and esker curves relate to one another.

The premise behind the examination of the esker-till lithologic curves (Fig. 34) is that till is the parent material of fluvioglacial debris. Rank tests (Table 7) on esker and till pebble populations for all indicator types, show that esker and till pebble populations are indistinguishable at the 95% confidence level, except for trough slate in Ashuanipi esker (not used in this section), and thus the premise is validated. Plots of indicator clast abundance in till and esker show that concentrations of clasts are not consistently greater in one material compared to the other (Fig. 34), indicating that there does not appear to be a mechanism by which enrichment or depletion can occur in the esker with respect to till.

If till and esker pebbles represent the same population, and no consistent enrichment or depletion occurs, then the concentrations of indicator clasts in an esker should be similar to that in till, and the difference between the compositional profiles offset can be used as an estimate of


A: Trough slate
Shabogamo esker
Western Labrador
★: Exit point
(wt)% : (wt)%/Maximum (wt)%
Distance from entry poiht (km)
-----: Till
: esker


B: Iron formation
Shabogamo esker
Western Labrador
(wt)% : (wt)%/Maximum (wt)%
Distance from entry point (km)


C: Volcanic rocks
Gabbro esker
Central Labrador
D: Quartz monzonite
Lac Brisson esker
Northern Labrador
(wt)%/Maximum (wt)%

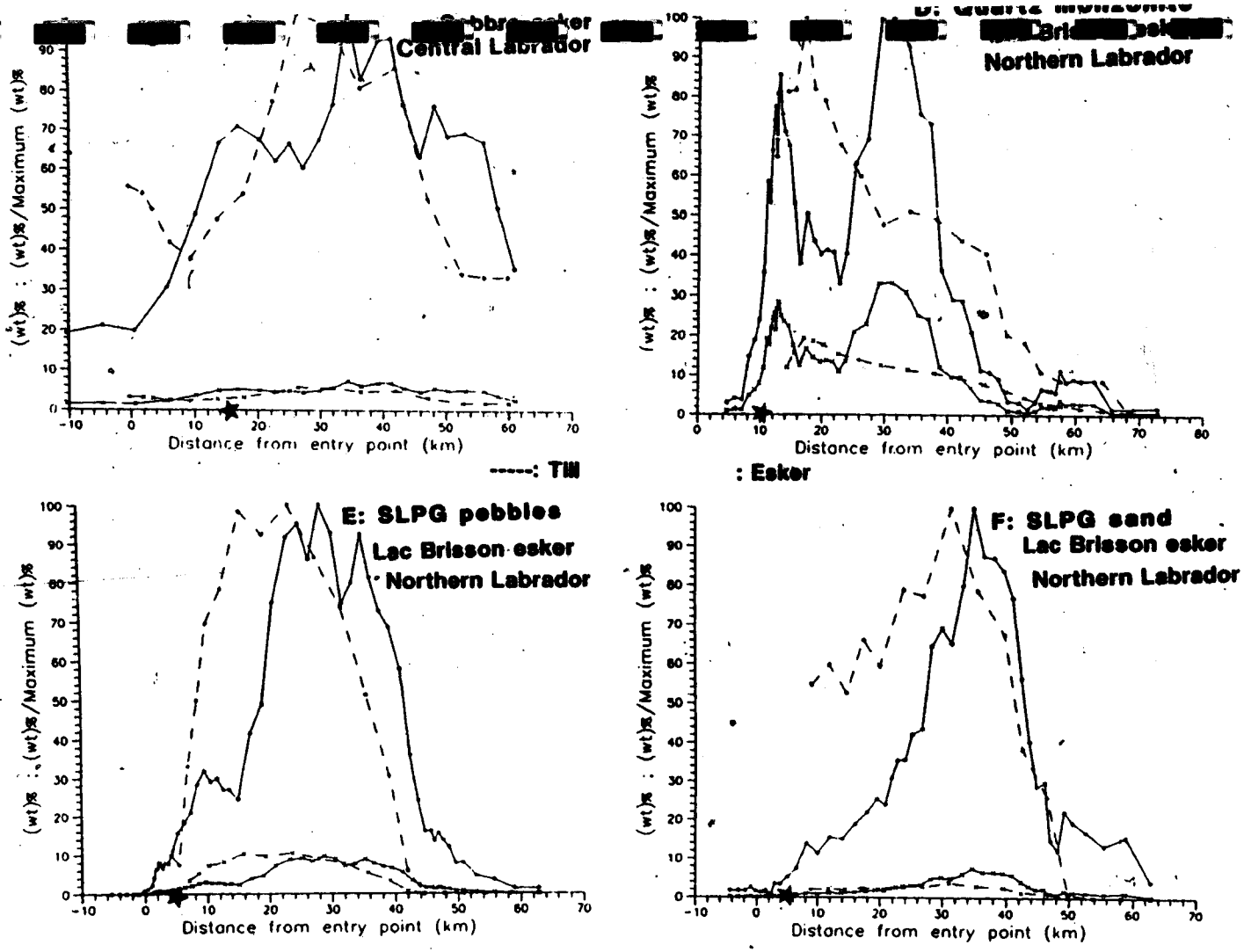


Figure 34. Lithologic curves (averaged data) according to material type. Direct plots (percentage vs distance, plotted as x) and standardized plots (percent/maximum percent vs distance, plotted as *) are shown. Distances are from the (projected) entry point, where the esker first crosses each bedrock type.

Central Labrador	Gabbro esker				Ossokmanuan esker			
	Cobbles		Pebbles		Cobbles		Pebbles	
Sample sizes	T=9; E=28		T=37; E=60		T=9; E=28		T=37; E=38	
	z	A/R	z	A/R	z	A/R	z	A/R
Sims quartzite	4.35	R	0.31	A	0.42	A	0.15	A
Arkose	1.85	R	0.10	A	1.00	A	0.64	A
Iron formation	2.27	R	0.44	A	0.63	A	0.24	A
Volcanic rocks	3.81	R	0.03	A	1.21	A	0.15	A
Slate	0.76	A	1.33	A	0.08	A	1.24	A
Western Labrador	Shabogamo esker		Ashuanipi esker		De Mille esker		Mocse Head esker	
Sample sizes	T=77; E=89		T=77; E=24		T=77; E=39		T=77; E=34	
	z	A/R	z	A/R	z	A/R	z	A/R
Iron formation	0.69	A	0.79	A	0.00	A	0.82	A
Trough slate	0.56	A	3.48	R	0.59	A	1.26	A
Northern Labrador	Lac Brisson esker							
	Pebbles				Sand			
Sample sizes	T=139; E=106				T=194; E=78			
	z		A/R		a		A/R	
Quartz-monzonite	0.0018		A					
Quartzite	0.0022		A					
Strange Lake peralkaline granite	0.0045		A		0.0016		A	

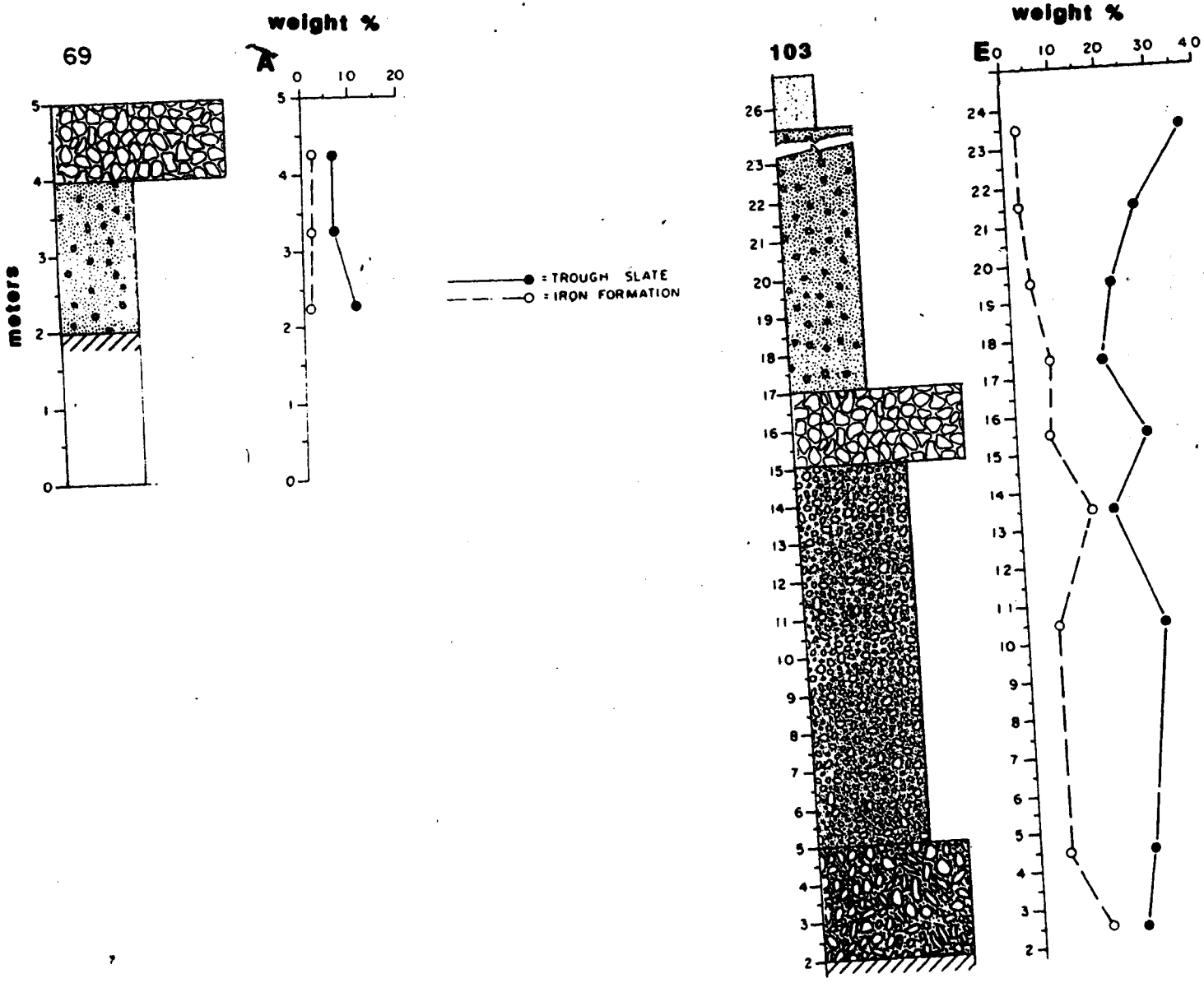
Table 7. Results of the rank tests (Snedecor and Cochrane, 1980) applied on till and esker samples for the same area, each lithology, and each size fraction. The factor «z» is a statistical measure based on the mean of each group (till vs esker), the number of observations, and the average and variance of the whole group (till and esker together). The hypothesis that till and esker samples are from the same population (A = accepted; R = rejected) was tested at the 95% confidence level. T = sample size for till; E = sample size for eskers.

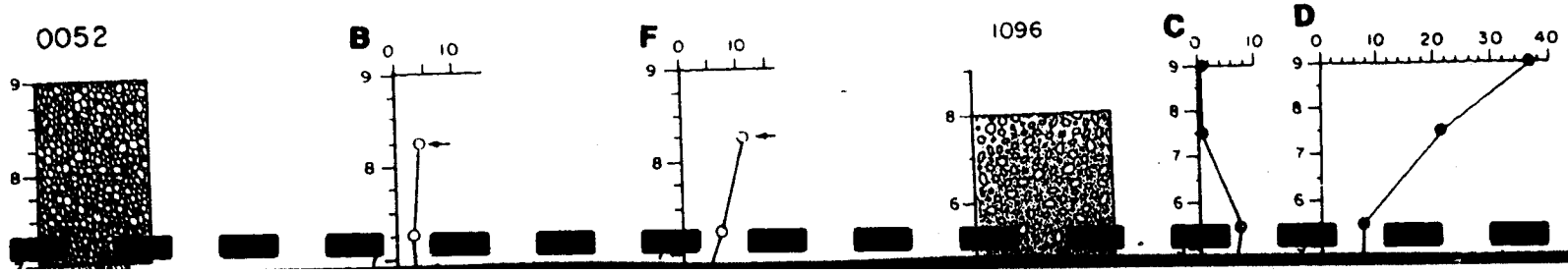
fluvioglacial transport. The average distance between till distribution pattern and esker distribution pattern is 10 km, ranging from only 4 km (SLPG sand, curve F, Fig. 34) to 19 km (iron formation, Shabogamo esker, curve B, Fig. 34), as shown by the standardized curves. The rates of increase and decrease with distance are generally greater in till than in eskers (standardized curves, Fig. 34), meaning that concentrations of indicator clasts in till augment more rapidly to maximum values, or decrease more rapidly from maximum values, than in esker.

Intuitively, there should be a difference in the offset depending on the topographic setting of the esker segment under study, and on the rapidity of glacial retreat. Ascending esker segments would have required a stronger flow to carry debris up-slope, and it is likely that the debris was sedimented rapidly. In flat or descending esker segments, transport could be longer. Under conditions of rapid retreat, shorter transport in the fluvioglacial system should occur, while under conditions of slow retreat, longer transport would have time to occur. Neither topographic control, nor speed of glacial retreat can be proven with the compositional data presented here, but the idea will be further tested when cluster analysis of till and esker data is discussed.

Vertical variations in lithologic composition

Sixteen sections were sampled to assess vertical differences in lithologic composition (Appendix 7). The shorter sections (<3 m, <4 samples; A, Fig. 35) and those sections located in the dispersal train distal area (B, Fig. 35) yield limited or no information on trends (enrichment or impoverishment) in an esker section. Sections 58 and 179 (Ossokmanuan esker); sections 67, 69, 70 and 71 (Shabogamo esker); sections 112, 113, 123 (Moose Head esker) do not have enough samples ($\leq$ 4) for a valid interpretation. Because sections 52 (Gabbro esker), 229 (De Mille esker), and 1076 (Lac Brisson esker) are located in the dispersal train distal area of indicator lithologies, their data are inconclusive. All other sections (103, 124, Moose Head esker; 1047, 1096, Lac Brisson esker), show indications of trends, although not necessarily for all lithologies. The distribution of volcanic rocks at section 52 (Gabbro esker), iron formation and slate at section 103 (Moose Head esker) and quartz-monzonite and SLPG pebbles at section 1096 (Lac Brisson esker) have been chosen because they are


weight %
69
A
0 10 20
meters
= TROUGH SLATE
= IRON FORMATION
103
E
0 10 20 30 40
weight %


0052
B
F
1096
C
D
0 10 20 30 40

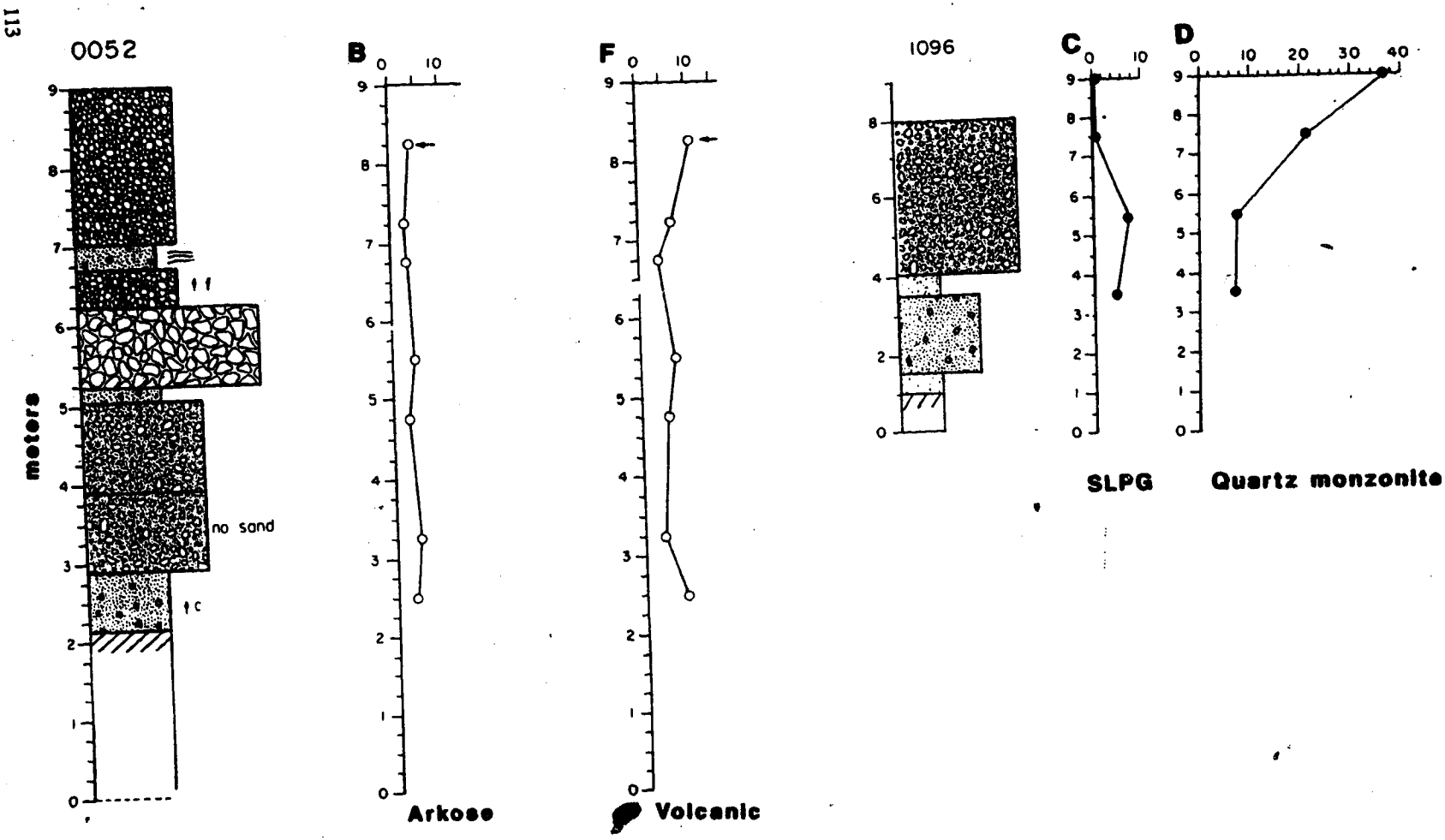


Figure 35. Vertical lithologic variations, pebble fraction. A: Trough slate and iron formation at section 69 (km 76.5 from entry point), Shabogamo esker B: Arkose at section 52 (km 80 from entry point) of Gabbro esker C: SLPG at section 1096 (km 3.5 from entry point) of Lac Brisson esker D: Quartz-monzonite at section 1096 (km 13.5 from entry point) of Lac Brisson esker E: Trough slate and iron formation at section 103 (km 36 from entry point) of Moose Head esker F: Volcanic rocks at section 52 of Gabbro esker.

the best examples of how lithology changes in an esker section (Fig. 35).

Indicator lithology proportions near the base of an esker section are related to local till, while proportions near the top of a ridge are related to till located 10-15 km up-esker from the section. The best example of this is shown by section 1096, Lac Brisson esker (C and D, Fig. 35). Even though till values are not available up-esker from where SLPG bedrock is located, they can be assumed to be 0 wt% for SLPG, and some high value for quartz-monzonite, since the till samples would have been located on quartz-monzonite bedrock. At section 1096, SLPG percentages near the base of the esker are in the order of 5-10 wt%, (local till: 3-5 wt%), while near the top, esker SLPG values are <1 wt% (up-esker till assumed to be 0 wt%). Conversely, quartz-monzonite near the base of the esker is about 6 wt% (local till: 10 wt%), and near the top, esker quartz-monzonite values are up to near 40 wt% (up-esker till assumed to have high quartz-monzonite values).

Another characteristic of vertical lithologic distribution is that the trend displayed down-section is commonly that which is found down-esker (crest) for 10-15 km. Accordingly, higher percentages in SLPG pebbles near the base of section 1096 (C, Fig. 35) are found in crest samples located at least 10 km down-esker, while low percentages in quartz-monzonite pebbles are found about 5 km down-esker from section 1096 (D, Fig. 35). In section 103 (E, Fig. 35), higher percentages in iron formation and lower percentages in Trough slate vertically (about 10 m from the top) are similar to crest samples about 5-10 km down-esker.

The profiles of thicker sections which may have up to 10 samples can be separated into shorter segments which each have an enrichment or impoverishment trend. The «cycles» may be associated with fluctuations in the glaciofluvial system, possibly yearly, and periodic erosion of the previously deposited sediment pile. Some of those cycles may be associated with sedimentary units (E, Fig. 35), but the sample spacing is usually too large to verify this assumption satisfactorily. The best example of this cyclicity is probably the distribution of volcanic rocks at section 52 (F, Fig. 35). Overall, the levels of volcanic rocks near the top are similar to till about 8 km up-esker, while near the base, volcanic rock percentages are about 5 wt%, closer to values in local till. In details however,

the distribution of volcanic rocks show two cycles of enrichment up-section, the top one may be correlated to crest samples about 3 km down-esker, while the other may be correlated with samples 7-9 km down-esker (Fig. 35).

The indications of vertical lithologic variations found in the few sections examined can be accommodated in a model of esker sedimentation analogous to the laying of shingles on a rooftop. Assuming a shingle has the same characteristic all along, but because it is deposited at an angle, the leading edge of a shingle which is found at the top of an esker should be similar to its trailing edge, located at the base of the esker some distance up-esker. The shingle model could also explain why esker pebble values near the base of a section are more closely related to local till, whereas pebble values near the top are related to till up-esker (Fig. 36). The offset between till values and esker crest values in a particular indicator lithology could be taken as a measure of the length of a shingle.

Effect of tributary junctions on lithologies of the main esker

At nine locations, both the tributary and trunk eskers were sampled near their junction to determine the effect of the tributary on the composition of the trunk esker. Most junctions, however, are located in the till dispersal distal area of indicator lithologies, and therefore, there are not enough differences in tributary and trunk composition (within counting variability) to make a difference in the composition down-esker from the junction. Twenty-eight (28) lithological curves (pebble distribution) across junctions could be generated (data in Appendix 7). Seventeen (17) curves do not show any significant differences in indicator levels between the tributary and trunk (A, Fig. 37), seven (7) curves show differing levels (significant at the 95% confidence level) of indicator in the trunk and tributary before the junction, but no apparent changes in the trunk down-esker from the junction (B, Fig. 37), and only four (4) indicate some effect of the tributary on the composition of the trunk esker (C to F, Fig. 37). The four curves which show effect of the tributary on the trunk are discussed below, and indicate that specific conditions have to be met for the composition of a trunk esker to respond to input of debris by a compositionally different tributary esker.

The junction between T1 and Gabbro esker occurs at km 9 of Gabbro esker (Fig. 37B), and

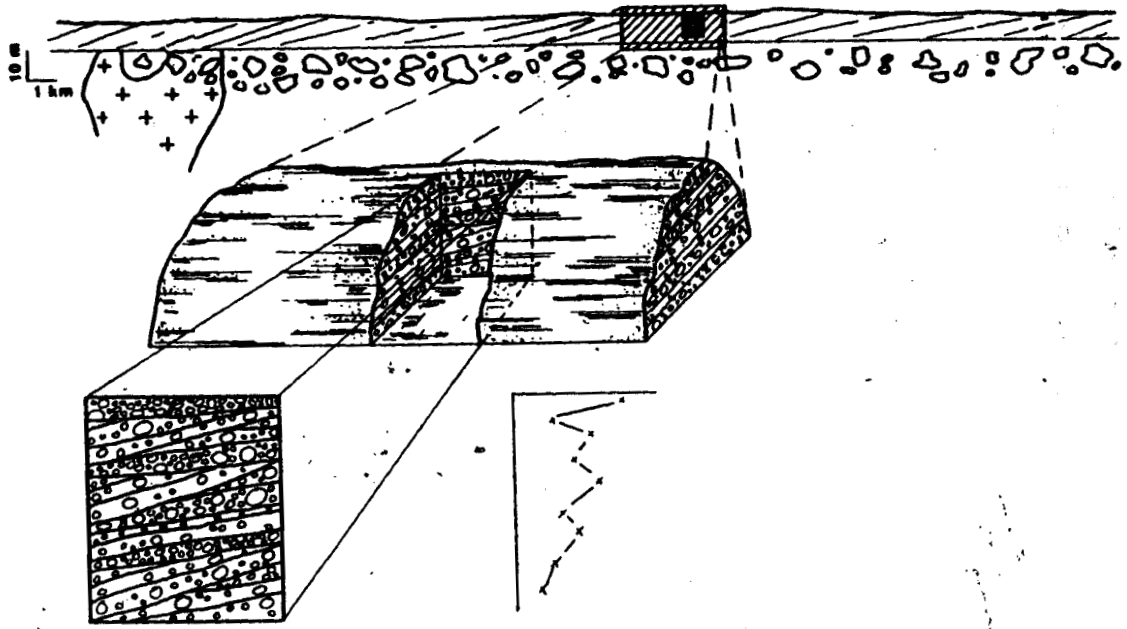
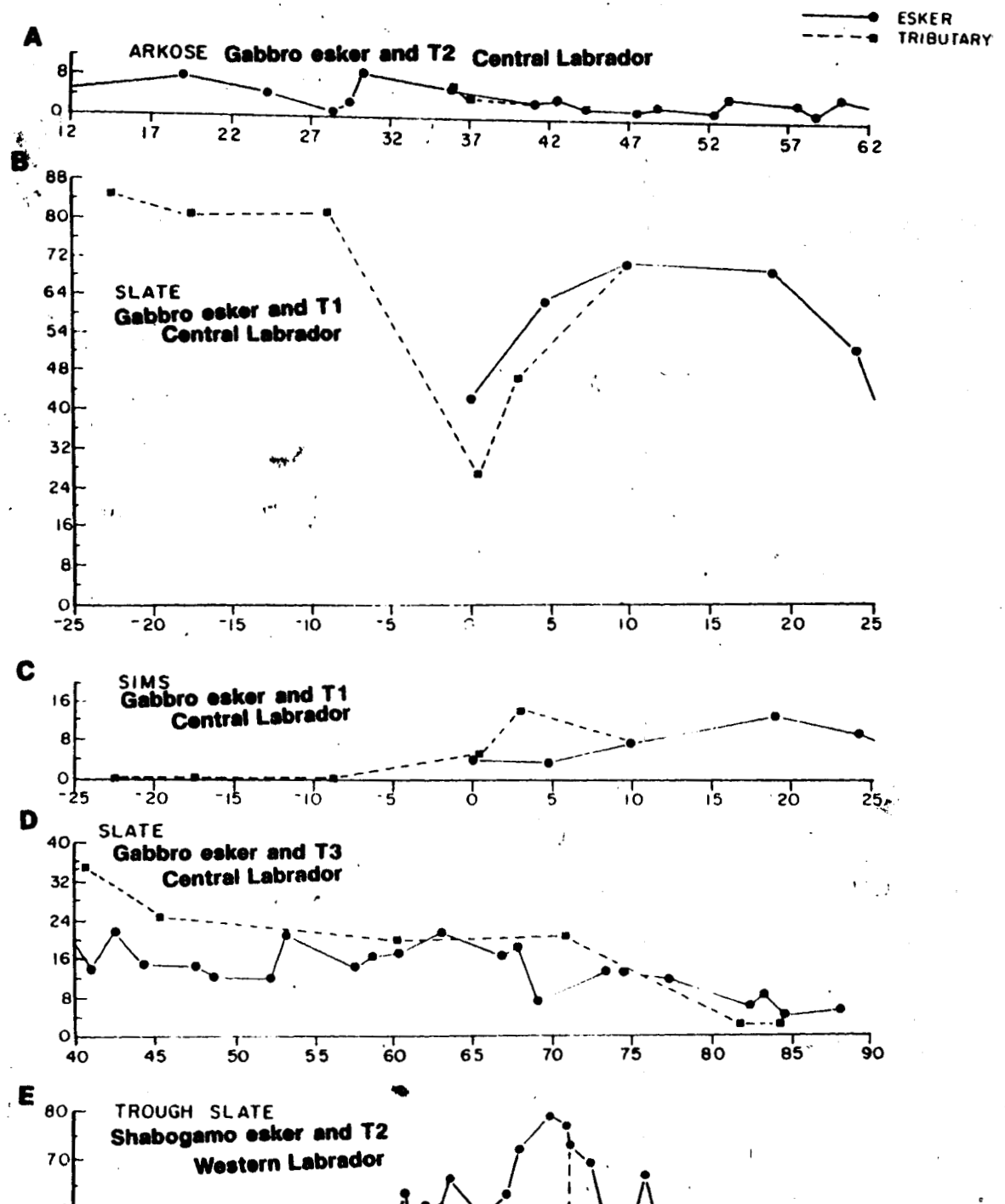


Figure 36. Shingling of lithologically similar units. Transport and deposition of debris in an esker tunnel is by long and thin sheets of debris which are deposited on top, but slightly set back from the down-esker portion of the previously deposited sheet, as in the laying of shingles. In this example, layers rich in component «X» are represented by those layers which have a high density of clasts drawn in. Lithologic counts in a theoretical section might produce a zig-zag pattern resulting from multiple deposition and erosion events.


ESKER
TRIBUTARY
A
ARKOSE Gabbro esker and T2 Central Labrador
B
SLATE
Gabbro esker and T1
Central Labrador
C
SIMS
Gabbro esker and T1
Central Labrador
D
SLATE
Gabbro esker and T3
Central Labrador
E
TROUGH SLATE
Shabogamo esker and T2
Western Labrador
Weight %

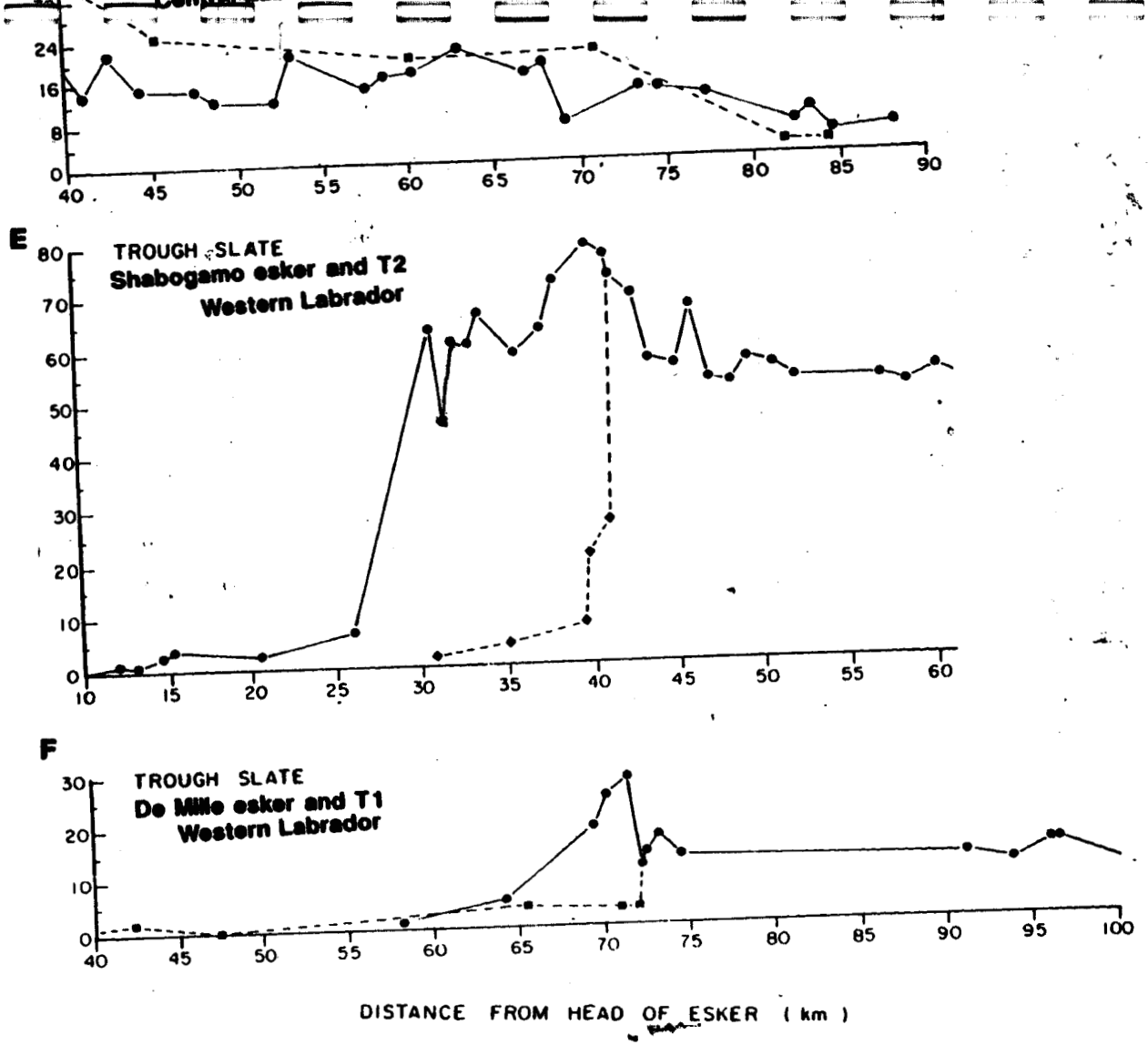


Figure 37. Influence of tributary eskers, pebble fraction. The trunk and tributary distributions join at the first sample after the junction.

the junction is by a 2 km long meltwater stream. In both eskers, the percentages of arkose, iron formation, volcanic rocks and slate are similar. T1, however, is located over the head of a Sims quartzite dispersal train, while Gabbro esker is located over the distal area of a different Sims quartzite dispersal train. The levels of Sims quartzite are higher in T1 (12 wt%) than in Gabbro esker (4 wt%) (C, Fig. 37). The sample immediately down-esker from the junction has intermediate percentage of Sims quartzite (8 wt%), possibly indicating some enrichment by the tributary. The following sample (located 10 km down-esker) has 12 wt% Sims quartzite pebbles, which is not likely related to the effect of the tributary, but to normal increase due to higher till values.

The junction between T3 and Gabbro esker occurs at km 84 of Gabbro esker, and the tributary and trunk physically touch (Fig. 37D). In T3 and Gabbro esker, the percentages of Sims quartzite, arkose and iron formation are similar. The levels of volcanic rocks are lower in T3 (<2 wt%) than in Gabbro esker (6-8 wt%), but the concentrations of volcanic rocks decrease before the junction, so that the tributary does not affect it. While the levels of slate pebbles in T3 and Gabbro esker are somewhat comparable (20 wt%), there is a sharper drop in T3 before the junction (from 24 wt% to <2 wt%) than in Gabbro esker (from 16 wt% to 8 wt%) (D, Fig. 37). At the junction, the levels of slate pebbles in Gabbro esker drop to 4-5 wt%, possibly indicating some dilution from the debris input into Gabbro esker by T3.

The junction between T2 and Shabogamo esker occurs at km 43 of Shabogamo esker. Shabogamo esker has a double ridge just up-esker from the junction, and one of the ridges touches T2. Levels of iron formation in T2 and Shabogamo esker are comparable. Levels of slate pebbles in T2 (25 wt%) and Shabogamo esker (75 wt%) are markedly different, but the interpretation of the distribution down-esker from the junction is ambiguous (E, Fig. 37). The first samples taken on T2 are not located on slate bedrock. Therefore, the slate distribution in T2 has all the characteristics of an entry curve, which is not complete because of the junction with Shabogamo esker. Shabogamo esker, however, has high levels of slate pebbles for 15 km before the junction. At the junction, the levels of slate pebbles drop slightly (to 55 wt%), either due to dilution by T2, or to the normal

decrease in indicator pebbles after peak values have been attained. If the rapid decrease in Trough slate in Shabogamo esker down-esker from the junction is indeed the result of dilution by T2, then projecting the lithological curve of Shabogamo esker before the junction at the same rate of decrease brings the curve to km 52 (E, Fig. 37), a probable esker length influenced by the tributary of about 10 km.

The junction between T1 and de Mille esker occurs at km 72 of De Mille esker. T1 and De Mille esker physically touch at the junction, and the trunk ridge is about twice as high downstream of the junction. The levels of iron formation in T1 and De Mille esker are similar. Possibly the most convincing example of the effect on the lithologic composition of a trunk esker by a tributary comes the distribution of Trough slate pebbles in T1 and De Mille esker (F. Fig. 37). Before the junction, the proportion of Trough slate pebbles in De Mille esker are low (< 4 wt%). Values for the trunk are higher (20-25 wt%) for the five kilometres before the junction, and the shape of the lithologic curve resembles an entry curve. At the junction, and from there on, Trough slate values are 10-12 wt%. The increase in Trough slate values from <4 wt% to 10 wt% at the junction, within less than 1 km is too rapid to attribute to normal enrichment to peak values. The sharp decrease from 26 wt% on the trunk esker to 10 wt% at the junction is also too rapid to attribute to normal dilution after peak values (which was a possibility for T2 and Shabogamo esker). The change in Trough slate levels down-esker from the junction is therefore the result of combining Trough slate-enriched T1 with Trough slate-deficient De Mille.

The data from the four previous examples indicate that tributary and trunk eskers contribute about equally to the sediment pile from the junction down-esker, but because the pebbles were separated from unknown different size samples (samples were sieved until at least 50 g of pebbles were separated), no direct volumetric relationship can be established. Because the lithological curves down-esker from junctions «blend» into the «normal» curve for the trunk esker with no particular break in the curve, it cannot be assessed from the data how far down-esker from the junctions the influence of the tributary is felt, with the possible exception of T2 and Shabogamo esker. If the 10

km segment on Shabogamo esker has indeed been influenced by T2, then it provides an estimate of the minimum length of esker tunnel active at that time.

Till - esker relationships

The debris in an esker can only come from bedrock, pre-existing Quaternary sediments, and till. Till is likely the predominant source, since in some cases the esker does not run over the indicator bedrock under study (ex. Sims Formation quartzite). Two-sample rank tests have been applied to till and esker data for each lithology at each size fraction, for the same sector, to verify that in fact till and esker sediments are the same populations. The result of the rank tests (Table 7) indicate that till and esker sediments (pebble and sand) are indistinguishable populations at the 95% confidence level. Where too few samples in till compared to esker were available (cobble data), differences between till and esker populations were identified at the 95% confidence level. For this reason, the relationship between till as the parent material, and esker debris, was investigated using the pebble and sand data.

The relationship between till samples and lithologically similar esker samples can indicate an overall distance of transport in the glacial and fluvioglacial system. Minimum transport distances in the fluvioglacial system alone can only be estimated from the distance between the point of exit of an esker outside a till dispersal train and where the last indicator fragment is found in the esker system. In the discussion of the results of cluster analysis, distance between a till sample and its most closely related esker sample lithologically can therefore not be taken as a direct equivalent of distance of fluvioglacial transport, but is a measure of the interpreted relation between till, as «parent» material, and esker sediment. An attempt to separate glacial from fluvioglacial transport follows the discussion of cluster analysis results.

Cluster analysis was applied to all data in the following manner. For each area, all till samples were treated with each esker system samples (2 analyses for central Labrador, 4 analyses for western Labrador, and 1 analysis for northern Labrador). Input data are the lithological information, output data are the cluster memberships. The analysis provided by SPSSX® was used, and, for Lac

Brisson esker in northern Labrador, all options supplied for linking samples (methods and measures) were tested. The average linkage within group with the squared euclidean measure gave results which, geologically speaking, made the best sense. These specifications were therefore used for all other analyses.

Cluster analysis applied to all till and esker lithological data for each of the main areas might be expected to give groupings (Appendix 8) in which a till sample is lithologically most closely related to one or more esker samples down-esker (Fig. 38). Glacial and fluvioglacial transport are assumed to be of similar overall direction, and no groupings of till and up-esker esker samples are considered. Groupings of only esker or till samples are not considered either because no interpretation on till-esker relationships can be achieved from them.

Ideally, and for better results in cluster analysis, till samples in an area should be distributed according to a pre-determined grid (eg. one till sample per 5 km^2), and eskers would be located somewhere in that area. Realistically, however, because till is not the surface material everywhere, and because logistical constraints existed, till samples were taken along eskers in central Labrador, along eskers and between eskers (one till sample per 100 km^2) in western Labrador, and along eskers and on a 4 km^2 grid in northern Labrador.

In central Labrador, the distance between «parent» till and the esker sample to which it was most closely related, varies between 3 km and 50 km (Fig. 38A), for an average distance of 15 km. Most of the till samples in central Labrador are located close to the esker, and the distance, laterally, between «parent» till and esker can only be estimated at <1 km. For both Gabbro and Ossokmanuan eskers, the general topographic setting is a wide, shallow valley, except very locally where some small topographic obstacles are present. In central Labrador, topography does not appear to be a factor in the distance between «parent» till and esker sediment.

In western Labrador, the distance between «parent» till and esker varies between 2 km and 15 km (Fig. 38B), for an average distance of 6 km. Shabogamo esker is at a slight angle (~20°) to late ice flow, and some till-esker relations involve till samples located up to 4 km away laterally from

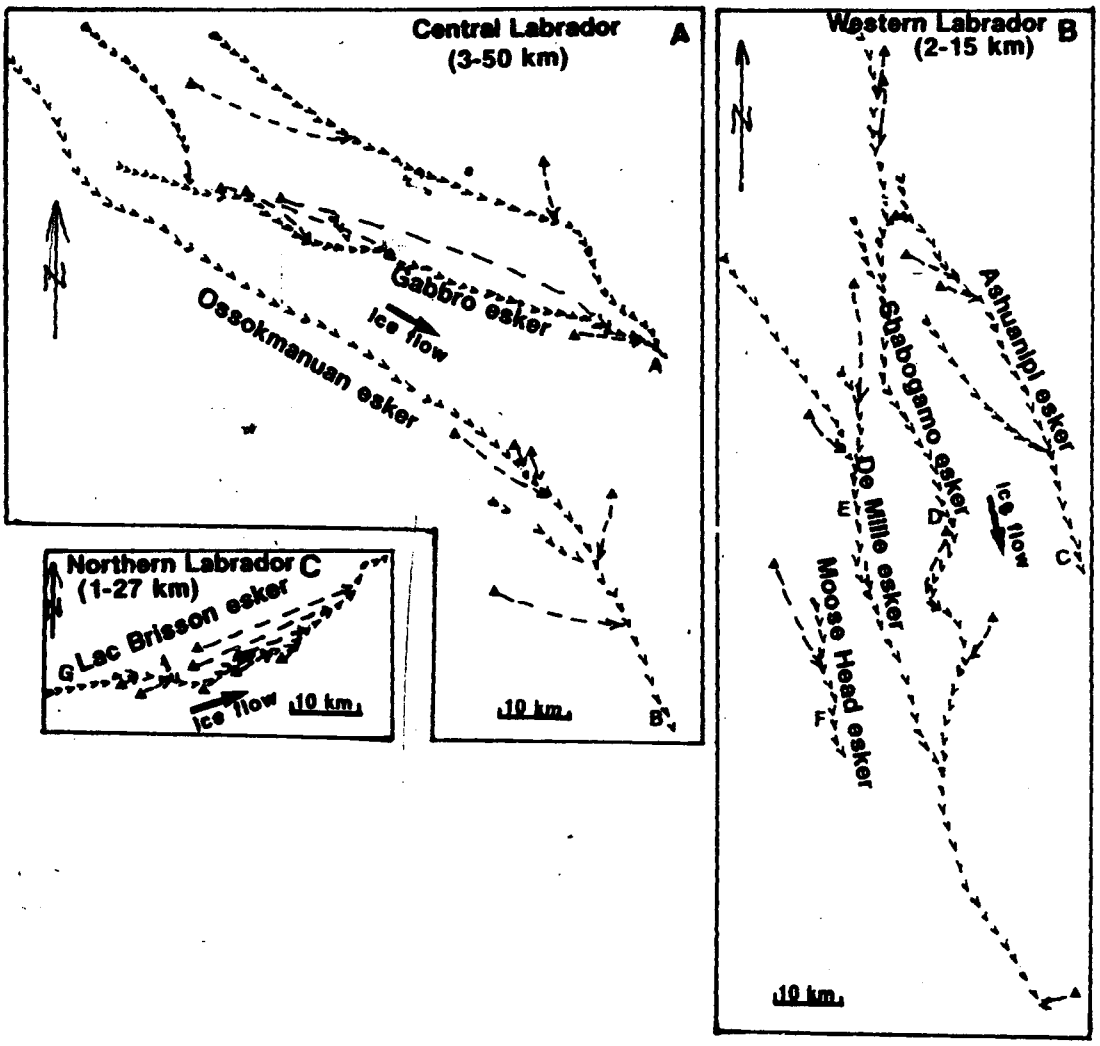


Figure 38. Distances between till and esker samples. The distances are derived from cluster analysis, for those samples (till and esker) which are compositionally similar. A) In central Labrador, the distance between parent till and compositionally equivalent esker sample varies between 3 and 50 km. B) In western Labrador, the distance between parent till and compositionally equivalent esker sample varies between 2 and 15 km. C) In northern Labrador, the distance between parent till and compositionally equivalent esker sample varies between 1 and 27 km.

the ridge, but in the general up-glacier direction. The shorter distances between «parent» till and esker in western Labrador compared to central Labrador do not appear to be related to topography, but may be due to a more rapid uncovering of the eskers, thus prohibiting relative extension up-glacier of tunnel segments in which esker sedimentation took place. The tunnels were not necessarily shorter, but they presumably were utilized for a shorter time.

In northern Labrador, results indicate that the distance between «parent» till and esker sediments varies between 1 km and 27 km (Fig. 38C), for an average of 11 km. «Parent» till is located either close to the esker (<1 km) south of the esker, or up to 4 km north of it. Two factors appear to have influenced distances between «parent» till and esker sediments in this area. Firstly, similar to western Labrador, segments of Lac Brisson esker are located at an angle (~30°) to late ice flow, and tills which are located far laterally from the esker are in fact directly up-glacier from the esker. Secondly, topography appears to have been an influence, such that the shortest distances are located close to the regional watershed, and also where tills are found on hills (local relief ~100 m) and the esker in the valley below. However, long distances of transport are found in reaches of the esker located in an area of essentially no relief.

While till and glacial debris in basal ice are the parent material of esker debris, it should be emphasized that the volume of till and glacial debris located directly beneath the path of the esker is not sufficient to account for the volume of sediments in the esker, especially if most fine grained debris (fine sand and smaller) is removed by the meltwater stream. It has been postulated (Shreve, 1972) and demonstrated (Repo, 1954; Veillette, 1986) that local ice movements, recorded by striae, towards a subglacial tunnel can be at a substantial angle (30°) to regional ice flow, as recorded by streamlined landforms and regional striae patterns. This local ice movement towards a subglacial tunnel provides a mechanism by which sediment can be added to the fluvioglacial system by melting out the debris in basal ice brought in by ice creep, and can also serve as an explanation for why esker samples in the preceding discussion of cluster analysis are related to till samples up to 4 km away from the ridge. The area on either side of an esker which theoretically would be affected by ice creep

is equivalent to half of the average distance between two eskers (6-7.5 km), such that ice drainage towards subglacial tunnels would exist. However, it is more likely that ice creep is most effective close to the tunnel, and progressively less effective away from the tunnel, such that there even might be a zone a few kilometres wide between eskers which is not affected by ice creep.

In Labrador, few outcrops are located close to esker systems, due to cover by associated deposits and till, and on most outcrops, weathering has obliterated any striae that may have been present. The only location where ice creep towards an esker could be confidently identified is in northern Labrador, on the south side of Lac Brisson esker. Along an esker reach situated in flat topography, at two locations, one about 500 m south of the esker, the other <100 m from it, two sets of striae indicate creeping of the ice towards the esker, more pronounced closer to it, but still at a low (10°) angle (Fig. 39A). Presumably, in a topographic setting in which the esker is located in a well defined valley, topography may enhance this local ice movement, thus increasing the angle of creep.

If till is the parent material of esker debris, and transport from bedrock to till to esker and down-esker is a combination of glacial and fluvioglacial activities, a path line from bedrock to till to esker can be established. Since striae indicate ice movement progressively warped towards the esker tunnel (Repo, 1954; Veillette, 1986; this study) debris must have followed an arcuate glacial path nearly parallel to regional ice flow in the first kms from the point of entrainment, then bending progressively towards the esker to a point of entry in the esker tunnel, followed by fluvioglacial transport to its final sedimentation location (Fig. 39B). The distance of transport in the tunnel depends on how far the ice margin is located from the point of entry, and how fast the esker segment is uncovered.

The lithologic composition of an esker can only reflect the lithologic composition of the till from which it formed, which in turn, is closely related to local bedrock. The first step in transporting debris is glacial, from bedrock source to a point, where it can be deposited as till with no further movement, or what can be referred to as «primary glacial transport» (Fig. 39B). During deglaciation, the presence of tunnels located at the base of the ice sheet can modify the path taken by glacial

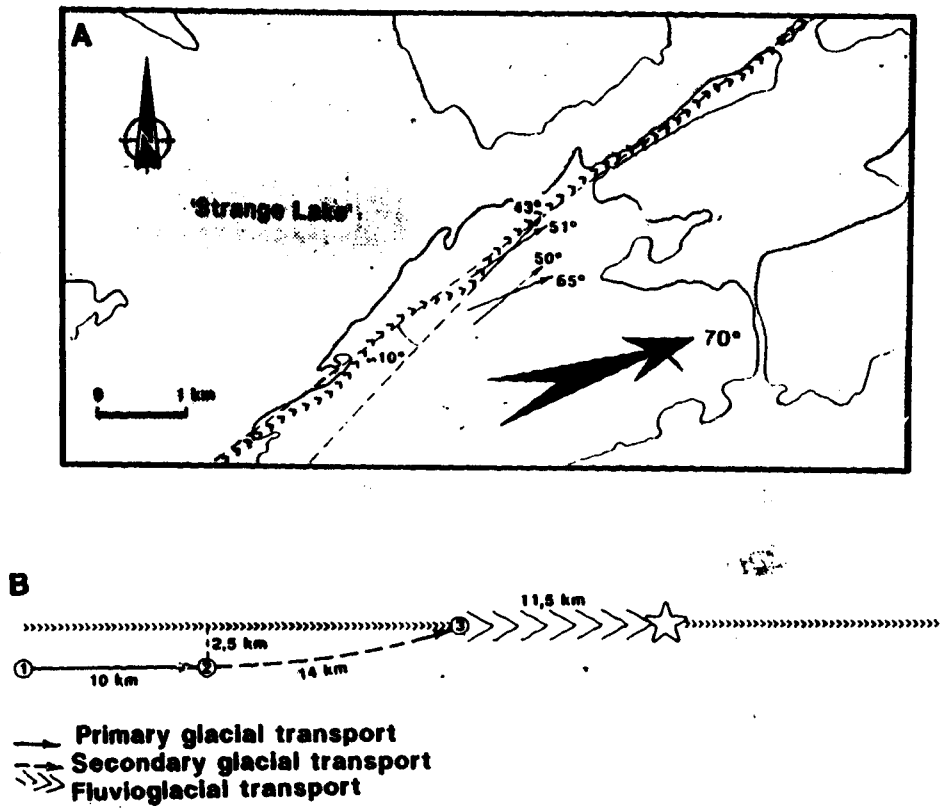


Figure 39. Ice creep towards an esker tunnel. A) Striae near Lac Brisson esker which show progressively stronger ice creep towards the esker tunnel. B) Theoretical model of debris entrainment from bedrock to till to esker, which involves three types of transport. Primary glacial transport is in the direction of regional ice flow, is accomplished before esker tunnels are emplaced, and carries debris from the bedrock source to a point where it may simply be deposited as till. Secondary glacial transport from till, is by ice creep towards and to an esker tunnel. Final transport is fluvioglacial in the tunnel.

debris, such that glacial debris is transported by ice creep towards subglacial tunnels, which is here called «secondary glacial transport» (Fig. 39B). Finally, when glacial debris is eroded out of the ice by flowing meltwater in a tunnel, it can be transported some distance in the tunnel before it is deposited as esker or associated deposit material, which is the strictly fluvioglacial transport (Fig. 39B). All other variables, such as topography and ice regime, being equal, the average distance between the lithologic assemblage found in an esker at any one point and its matching till site, becomes the average overall distance of transport influenced by an esker-forming tunnel (secondary glacial transport by ice creep operating first), and an estimate of the length of opened tunnel.

The best estimate of length of opened tunnel, and more specifically of fluvioglacial transport, comes from northern Labrador, where Lac Brisson esker exits SLPG and quartz-monzonite dispersal train. If the edge of SLPG (Batterson, 1989) and quartz-monzonite dispersal trains are taken to be the projection at 070° (regional ice flow) of the northern edge of the bedrock source (Fig. 32), then the distance beyond that point to which SLPG or quartz-monzonite debris is found is a minimum approximation of fluvioglacial transport distance. It is a minimum distance because indicator debris may have been in the system before the point of exit out of the till dispersal train, but it could not be entrained after the point of exit. SLPG cobbles are found up to 12.5 km from the estimated edge of SLPG dispersal train, SLPG pebbles, 25 km, SLPG sand, 30 km, and quartz-monzonite pebbles, 30 km. The presence of progressively finer-grained SLPG material away from the edge of the dispersal train may indicate comminution, and also indicates an opened tunnel of at least 30 km. The length of opened tunnel may depend on the rapidity of ice marginal retreat, and activity of the ice, such that esker tunnels are likely to be shorter in a rapidly deglaciated area with an active ice sheet, as opposed to longer tunnels in a slowly deglaciated area, or where the ice sheet is sluggish to stagnating.

ESKER FORMATION

The composite sedimentation model for eskers in Labrador derived from all data and observations collected could not have been obtained from one type of evidence only. The three

premises to the sedimentation model come from the literature and intuitive reasoning, and are supported by data collected in this study. The first premise is that esker sedimentation is assumed to occur in subglacial tunnels with highly variable water flow, including periods of full-tunnel flow and intervals of open channel flow (daily and seasonal meltwater flow fluctuations, Shreve, 1972). The second premise is that esker debris is derived from the base of the glacier because that is where deposited till and most glacial debris are found (Lawson, 1979). The third premise is that sedimentation has to occur near the margins of the ice because there needs to be input to the subglacial system of supraglacial meltwaters, and the maximum depth of moulins, the main route of supraglacial meltwaters downward, appears to be 25-30 m (Sugden & John, 1976, p. 289). While this is likely an underestimation of ice thickness, even near the edge of the ice sheet, it however implies that eskers are formed near the ice margin if supraglacial meltwater is to contribute to the subglacial system. Before presenting the model of esker formation, evidence from data presented previously will be reviewed.

The distribution of integrated esker segments in Labrador suggests that the path of eskers mimics that of the subglacial drainage system, as subtle subglacial topography appears to have had important control on local esker segments (pp. 66-67). Overall, however, the orientation of eskers is controlled by ice surface gradients, which is why eskers radiate away from the presumed ice divide in Nouveau Québec. Eskers are also usually parallel to streamlined landforms, which indicates that they were formed under essentially the same ice sheet configuration as that which formed the streamlined landforms, and that the ice was likely active (pp. 58-60). While supraglacial and englacial meltwaters contributed to the overall system, esker paths reflect subglacial meltwater escape routes. Local conditions may be very important in determining esker paths, as is demonstrated by those eskers which cross the George River valley.

Esker morphology suggests that ridges are deposited in contact with ice walls, likely as tunnel deposits, while associated deposits are deposited later than the adjacent ridge, in contact or not with ice, in a proglacial environment (pp. 74-75). Esker ridges may be deposited near the ice margin, or

at least in an area where ice creep is not rapidly effective to shrink a tunnel which would induce faster flow and remobilisation of the deposited sediments. Associated deposited are deposited in areas of unconfined (or less confined than tunnel conditions) flow, because they are composed mostly of fine grained sediment, which implies a marked flow decrease compared to tunnel conditions.

The coarseness of esker sediments, and general lack of fine-grained (silt and clay) material, indicates a high energy stream was responsible for the transport of debris in a fluvioglacial system, and winnowing of finer grained debris. Even if the till was originally composed of coarse debris, transport of large clasts in a fluvioglacial stream would abrade and break the clasts to produce smaller ones, and fine-grained debris. Esker stratigraphy shows that eskers are deposited by highly variable meltwater streams. The succession of sedimentologically different units within a single esker cross-section represents the variable flow conditions, which may be cyclic (pp. 81-88). Associated deposits appear to be deposited by a less competent stream than esker ridges, because of the finer grained, and more homogeneous nature of the deposits. The stratigraphy reinforces the morphology, that eskers are tunnel deposits, and associated deposits are proglacial deposits in a relatively unconfined environment.

The evidence brought forward on esker sedimentation by lithological analysis is complex, but a few points can be brought out. Esker lithologic composition is dependant on till composition, and the position of an esker in relation to a till dispersal train (near the edge, well inside, close to the source, or far away) are very important in determining variations in esker composition (pp. 98-100). The size and the erodibility of the bedrock source, due to factors related to glacial erosion, also influence how much of an indicator lithology is found in an esker. When all possible sources for an indicator lithology are shut off, that is when an esker crosses out of a till dispersal train, the indicator lithology is found in the esker for up to 25 km from the exit point (pp. 103-106). Cobbles disappear first, followed by pebbles, finally by sand. Nevertheless, esker tunnel transport had to occur over at least 25 km to explain the presence of indicator rocks 25 km away from the closest source. Since breakage was not found to be an important mechanism (pp. 107-109), this pattern may indicate that large clasts are deposited first, and smaller ones later, an indication of a decrease in stream

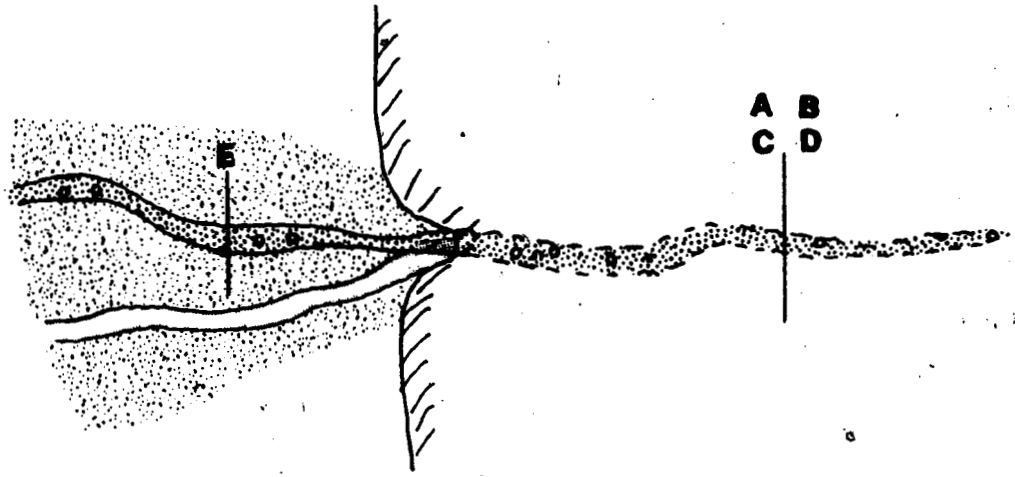
competence down-esker, which may be associated with widening of the tunnel near the ice margin.

Till being the parent material of esker, the proportions of lithologic indicators in esker are controlled by their initial proportions in till. Rank tests show that esker and till are the same population, and the distance between till distribution patterns and esker distribution patterns can be taken as a measure of transport from till to esker, separated in secondary glacial transport and fluvioglacial transport (pp. 109-112 and 120-126). Because the most abundant sedimentary units in eskers are the mixed units, fluvioglacial transport likely occurred as a sliding bed, or a slurry of sediments which effectively protected the larger clasts from breakage.

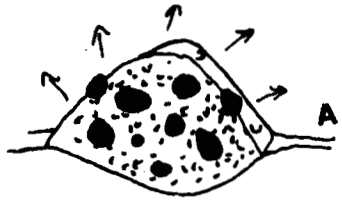
Vertical lithologic composition of esker ridges indicates that the base of an esker is similar compositionally to local till, while the top relates better to till located 10-15 km up-esker (pp. 112-115). Esker sediments are deposited in sedimentary units acting as «shingles». Each shingle is laid on top of, and slightly backset, the previously deposited unit. The shingling of sedimentary units can best account for the vertical lithologic composition seen in esker sections. Where tributary eskers, compositionally different than the trunk esker, merge with the trunk, the composition of the trunk is altered for 5-10 km (pp. 115-120). A complete hydraulic connection between the tributary and the trunk must have been present, even though there may not be a physical contact between tributary and trunk eskers now.

Model of sedimentation

The formation of an esker segment may occur as follows (Fig. 40). Over a one year cycle, just before spring thaw, the tunnel cross-section is at its smallest (Fig. 40B). Full tunnel flow during spring thaw caused by the discharge of large quantities of supraglacial meltwaters, entrains sediments previously deposited in the tunnel, and the flow of meltwater frictionally erodes the tunnel ice walls and ceiling, releasing englacial debris. During the period of high capacity and high competency flow, large boulders can be transported. As the tunnel cross-section enlarges to adjust to increased meltwater flow, and as the input of meltwater decreases after spring thaw, open channel flow may start, and the larger clasts are deposited on the floor of the tunnel.



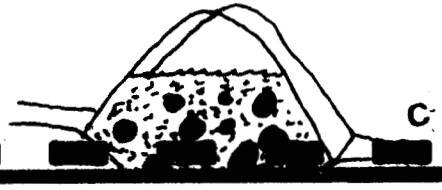
A: Spring high discharge event, when full tunnel flow initiates frictional erosion of the tunnel ice walls and roof, thereby releasing debris present in the ice, possibly eroding previously deposited sediments, and enlarging the tunnel.



B: Equilibrium between frictional melting and ice creep, during late spring and most of the summer. Full tunnel flow, transport of debris as a sliding bed.



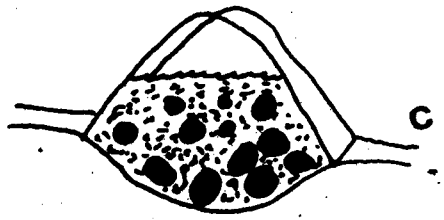
C: Reduced flow during late summer and early fall marks the start of open channel flow, deposition of the coarse load, and further transport of the fine load.



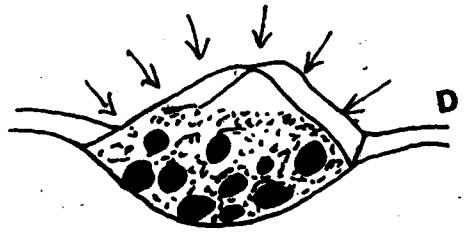
D: During fall and winter, conditions of no flow and freezing may produce icing of the sediments, which may protect the deposits from further erosion during the next spring high discharge event. And the cycle starts over again, until the esker is uncovered.



marks the start of open channel flow, deposition of the coarse load, and further transport of the fine load.



and freezing may produce icing of the sediments, which may protect the deposits from further erosion during the next spring high discharge event. And the cycle starts over again, until the esker is uncovered.



E: When the esker is uncovered, the final deposit is a mixture of size fractions, with distinct layers such as the boulder bed and heterogeneous units.

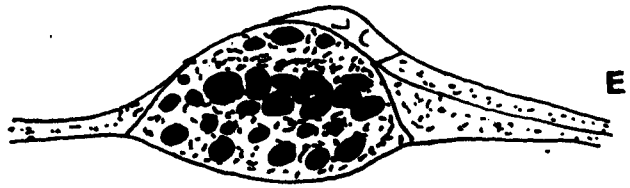


Figure 40. Theoretical model of esker sedimentation. Over a one year period, A) full tunnel flow in the spring in response to spring thaw frictionally enlarges the esker tunnel, erodes and transport the largest debris. B) Equilibrium between meltwater discharge and ice creep during the summer serves as the main transport for the bulk of esker debris. C) During open channel flow in the fall, the smaller debris is transported, while the coarser debris is deposited. D) Conditions of no flow and freezing in the winter can act as a protector for the following spring high discharge event. E) The final deposit is a mixture of coarse and fine debris, with distinct layers such as the boulder bed and sand layers.

During late spring and summer, the tunnel cross-section continues to adjust to meltwater flow, and daily fluctuations, as well as input from precipitations, may determine an alternation between full-tunnel flow (more vigorous flow during the day or after precipitations, and open-channel flow (less vigorous flow during the night). During full tunnel flow (Fig. 40C), transport of debris as a sliding bed, as postulated by Saunderson (1977), which is deposited during periods of open channel flow (Fig. 40D), accounts for the presence of the matrix supported units so common in the esker ridge. Removal of the finer material continues during this time, and thus, fine grained sediment is transported farther than coarse debris, likely to the margin of the ice sheet, where it is deposited as associated deposits on either side of the esker, or transported away in the proglacial stream.

In the fall, meltwater flow slows down considerably as much of the surface meltwater which is believed to be a large contributor to esker forming streams, freezes at the surface and does not reach the subglacial system. Greatly diminished flow in subglacial tunnels during that time may trigger the deposition of the finest sediment. Meltwater flow may cease entirely during late fall and winter near the ice margin, and sediment may freeze from cold air penetrating into the tunnel. Subglacial meltwater flowing from the interior of the tunnel may also freeze, forming a protective layer on top of the sediments already deposited. Tunnel size decreases markedly if the ice is still active, or only slightly if the ice is nearly stagnant, until spring thaw arrives again, and the cycle starts over. Erosion of previously deposited sediments during spring thaw may be prevented by the protective ice layer formed during the winter, a mechanism by which beds of fine grained material may be found in an esker ridge.

As the subglacial stream emerges at the ice margin (Fig. 40E), it is no longer confined, or its confinement is reduced, leading to a spreading of the stream, loss of energy, and deposition of the coarse debris. The fine debris is carried in the proglacial river as a normal river load, and is deposited as a sandur in front of the glacier. Some of this outwash deposit may cover the esker, especially if the sandur is deposited at the surface of the glacier. As buried ice melts, the esker emerges from the sandur. Aprons, pads, splays and blankets are deposited as proglacial river deposits for those ice

margins which terminate on land.

Because of the inference from lithologic data in vertical section that basal esker sediments are derived from local till (pp. 112-115), while sediments from the surface come from more distant till, sedimentation of an esker ridge appears to be accomplished by the laying of long tabular sedimentary units (Fig. 36). The deposition of the units would take a form similar to the laying of shingles, on top but slightly behind the last unit deposited. The length and thickness of a shingle may be highly variable, depending on the available sediments, the distance from the ice margin where the shingle is being formed, and the rapidity of ice retreat, and therefore of uncovering of the esker ridge. Moreover, re-entrainment of sediments during high flow events associated with precipitations, for example, may move debris farther in a different shingle than its original one. The angle of climb of a shingle is low, as in sections, most units appear to be nearly horizontal. Estimates, using the distance between similar basal esker samples and crest samples (~ 10 km, pp. 112-115)) and the average height of eskers in Labrador (12 m, p. 48)) indicates that the angle of climb is $<1^{\circ}$.

Sequence of formation

Recent estimates for the timing of the deglaciation of the Labrador-Nouveau Québec Peninsula (King, 1985; Dyke and Prest, 1987; Clark & Fitzhugh, 1990) can be used to roughly estimate the amount of time that some of the larger eskers had to form. The estimate of time needed to form eskers is rendered difficult due to two factors. Firstly, while eskers were formed by the time the area was deglaciated, it is not known when, in time, they started to form. Placing the start of esker formation when the ice margin was located at their down-esker end may not be accurate, and therefore, estimates are minimum. Secondly, because basal dates represent the time of colonization by the vegetation of the site, rather than the time of deglaciation, the length of time for the formation of eskers are over-estimated, unless, if the lag time is constant, then it averages out.

Based on the time of deglaciation at the down-esker end of Lac Brisson esker (the 10,000 yrs BP ice marginal position of Dyke and Prest (1987), reevaluated by Clark & Fitzhugh (1990) to 7500 to 7700 yrs BP) and on the time of complete deglaciation of the area (^{14}C date of 8160 ± 925 yrs BP

on basal sediments on the Kogaluk Plateau by Short (1978) is considered too old (Clark & Fitzhugh, 1990) and thus deglaciation may have happened only about 7000 yrs BP) Lac Brisson esker and others in northern Labrador, were formed in a minimum time of 500 to 700 years, and a maximum of 3000 years. Lac Brisson esker is about 100 km long, so that it was built and uncovered at a rate of 30-40 m/yr, to 200-250 m/yr. The rate of uncovering may not have been the same as the rate of building, esker segments may have been abandoned at the ice margin where stagnant ice could not creep to compensate for enlargement of the tunnel by frictional melting. Meltwater would have flowed on either side of the esker without contributing sediments to the deposit.

Using the same method of estimation as above for central and western Labrador, and based on isochrons constructed with radiocarbon dates corrected to estimate deglaciation (King, 1985), most eskers in central and western Labrador would have been built within a few 100 years, up to 700-800 yrs. Since esker lengths are in the order of a few hundred kilometres, a very rough estimate of the rate of esker uncovering is in the order of 250-300 m/yr.

While the esker construction rates given here are maximum, the rapidity of building of eskers is in keeping with the notion that fluvioglacial systems are «more» in terms of physical characteristics than normal fluvial systems. Fluvioglacial systems have higher discharges and velocities, have highly variable flows, transport much more debris, and much larger debris than fluvial systems.

CONCLUSIONS

The study of eskers in Labrador has contributed to the knowledge of fluvioglacial systems which cover large areas of continentally glaciated terrain by stressing that the development of esker systems is in direct response to constraints imposed on the melting ice sheets by the glacier itself (need to evacuate meltwater), subglacial topography (exploitation of low lying routes where available) and the presence and amount of debris (no debris in the ice, or deposited till means no eskers can form). The aim of the research was to present an esker sedimentation model which would account for the data and observations recorded during the work, with special interest on esker distribution, relationship to underlying topography and ice sheet morphology, external morphology, internal

stratigraphy, and lithologic composition with respect to till and bedrock.

The distribution of eskers shows three different types of organization. The first type of organization is those sectors in which few to no eskers are located, representing areas nearly devoid of glacial sediments (such as the Harp Lake Massif), areas where meltwaters were evacuated in valleys oriented parallel to ice flow and with a positive gradient, so that esker sedimentation did not take place, or in areas where ice might have been to thin to keep a coherent drainage network, and therefore, eskers were not formed. The second type of organization is represented by those areas in which eskers are found, but do not reflect an organization of the drainage of the ice sheet, and are the result of rapid deglaciation in an area where debris was available, but time for structuring the drainage was lacking. The third type of organization is represented by those sectors in which eskers form a sub-parallel dendritic network reflecting that part of the glacier which stayed relatively stable for a long enough period of time to allow the formation of a subglacial tunnel system.

The tunnels functioned as an integrated meltwater escape route controlled by the ice surface gradient (eskers are sub-parallel to late ice flow) influenced by subglacial topography (detour around topographic obstacles, junction between eskers to exploit the best possible hydraulic route). Connections between all parts of a system within a drainage basin is demonstrated by the influence on lithologic composition a tributary esker has over a trunk esker.

The tunnels evacuated meltwater from the subglacial, englacial and supraglacial systems near the ice margin, where esker sedimentation took place, while further back, only subglacial meltwaters were present. The tunnels in which only subglacial meltwaters flowed were small, and followed subglacial valleys as long as they were oriented more or less parallel to ice flow (ice surface profile controls the flow of meltwater). Away from the ice margin, only meltwater flow in the tunnel occurred, while near the ice margin, strong fluctuations in meltwater discharge triggered enlargement and shrinking of the tunnel. During high flow events, erosion and transport of till and glacial debris resulted, while during low flow events, sedimentation of the esker ridge could take place. Morphologically, eskers are tunnel deposits, with steep flanks, and the internal stratigraphy attests to

the fluctuating meltwater flows. While eskers are tunnel deposits, there may be periods of open channel flow at any time during esker formation, and some eskers which have a flat, level, sandy surface may represent an open channel deposit at a late stage of esker formation. Fine grained material was carried out the tunnel with meltwaters, and was sedimented on the flanks of eskers, some time after the formation of the ridge itself. Associated deposits have morphologies and a more homogenous grain size distribution than eskers which indicate relative unconfinement of the meltwater stream compared to esker ridges.

The lithologic composition of eskers is strongly related to till lithology. The variations in composition along an esker ridge can be related to proximity of the source in bedrock, thus location in the head of a till dispersal train, size of the source, larger sources influencing more, and for longer distances, esker composition, and location of the esker within the till dispersal train. Vertical lithologic distribution indicate that esker sediments are deposited in long, shingle-like units which likely retain their compositional characteristics longitudinally. The location of a clast in an esker is the composite travel from bedrock source to till (primary glacial transport) to the fluvioglacial system (secondary glacial transport by ice creep) to deposition of the clast (fluvioglacial transport *per se*).

Evidences bearing on the length of active tunnel at any one time point to different answers, and may serve to emphasize that esker formation may be very dependant on local conditions. From lithological data for Lac Brisson esker (northern Labrador) with respect to SLPG and quartz-monzonite dispersal outside the till dispersal train, it is evaluated to be about 25 km. For the same esker, however, but based on the presence of esker segments up the George River valley and the presumed position of the ice margin at the head of Anaktalik Brook, an actively sedimenting esker tunnel may have been 100 km long.

There remains much to be answered on esker sedimentation. This research has generated some hypotheses which will need to be tested at carefully chosen sites in order for more elements on the origin of eskers to be put together. The quantification of esker parameters, size of drainage basins, importance of subglacial topography, are all aspects which were touched upon on a qualitative

to semi-quantitative basis, but would need a research plan differently set up to achieve. Finally, the dissection of an ideally located esker with respect to indicator bedrock and till dispersal train might clarify the concepts of shingling of esker sedimentary units, as well as the role of the different phases of transport (primary and secondary glacial, and fluvioglacial) in the dispersal of clasts in fluvioglacial systems.

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VITA

Name: Andrée Monique Bolduc
Born: June 7th, 1960 in Hull, Québec, Canada
Parents: Madeleine Marcoux and Gaston Bolduc

EDUCATION

Lehigh University, Bethlehem, Pennsylvania
PhD, 1992 — The formation of eskers based on their morphology, stratigraphy, and lithologic composition, Labrador, Canada

Carleton University, Ottawa, Ontario
M.Sc., 1985 — Quaternary History of the Churchill Falls area, Labrador

Université d'Ottawa, Ottawa, Ontario
B.Sc.h. 1982 — Géologie Quaternaire d'une région près de Thurso, Québec

WORK EXPERIENCE

Geological Survey of Canada

- Since 1989 — Research scientist, Centre Géoscientifique de Québec. Surficial mapping and synthesis of geo-information available to date on the Quaternary of southern Québec
- Summer 1987 — Party chief with 3 assistants, and a helicopter pilot on occasions. Esker investigation, western and northern Labrador; air photo interpretation; esker and till sampling and mapping; sample preparation; cobble, pebble and mineral counts.
- Summer 1986 — Party chief with 1 assistant, and a helicopter pilot on occasions. Esker investigation, central Labrador; air photo interpretation; esker and till sampling and mapping; sample preparation; cobble, pebble and mineral counts.
- Summer 1985 — Quaternary air photo mapping, Labrador. 18 NTS map sheets 1:250 000 scale.
- Summer 1984 — Camp manager, Flowers River project, Labrador. Responsible for conducting the till sampling program with 3 assistants and a helicopter pilot.
  Lab work: preparation of samples for geochemical analysis; pebble counts on a portion of the 1983 samples.
- Summer 1983 — Party chief with 1 assistant, and a helicopter pilot on occasions. Quaternary air photo mapping of the Churchill Falls area, Labrador, scale: 1:100 000. Quaternary sediment sampling and mapping; pebble counts for provenance studies.
- Summer 1982 — Pebble counts on till samples from the Frontenac Arch, Ontario; till sampling in Gatineau County, Québec.

Self employed

- 1988 Special service contract with the Maine Department of Conservation (Maine Geological Survey) for the surficial mapping of the North Windham 7½' quadrangle, Maine (1:24 000).

- 1988 Three month personal service contract with Energy, Mines and Resources, Canada (Geological Survey of Canada) for the identification of rocks and minerals from glacial sediments, Labrador. A binocular microscope, UV light, magnet, dilute HCl and others were used in this project.

Anaconda Canada Exploration Ltd., Vancouver, British Columbia

- Summer 1981 Bedrock mapping and sampling for gold exploration, northern Ontario; supervision of percussion drilling; drafting

Amok Ltd/Ltée, Saskatoon, Saskatchewan

- Summer 1980 Geophysical exploration for uranium using a SPP2 scintillometer, Carswell Lake, northern Saskatchewan; bedrock mapping and sampling; drafting.

TEACHING EXPERIENCE

Lehigh University, Bethlehem, Pennsylvania

- 1986-1989 Teaching assistant for: Environmental Geology; Introductory Geology; Crystallography (optical); Petrology and Petrography; Paleontology.

Carleton University, Ottawa, Ontario

- 1982-1984 Teaching assistant for Paleontology I & II; Stratigraphy I & II.

PUBLICATIONS

Bolduc, A.M.; Meglioli, A. and Thompson, W.B.; in press; Surficial geology of the North Windham Quadrangle, Maine; Maine Geological Survey Open File Report

Bolduc A.M.; Compilation cartographique des dépôts de surface dans le sud du Québec; Affiche présentée à l'APGGQ, avril 1992

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Bolduc, A.M.; 1992; Mineral exploration in glaciated terrain, some examples from Labrador; conférence présentée dans le cadre d'une tournée de conférences parrainnée par le chapitre des Maritimes de la Canadian Institute of Mining and Metallurgy; février 1992

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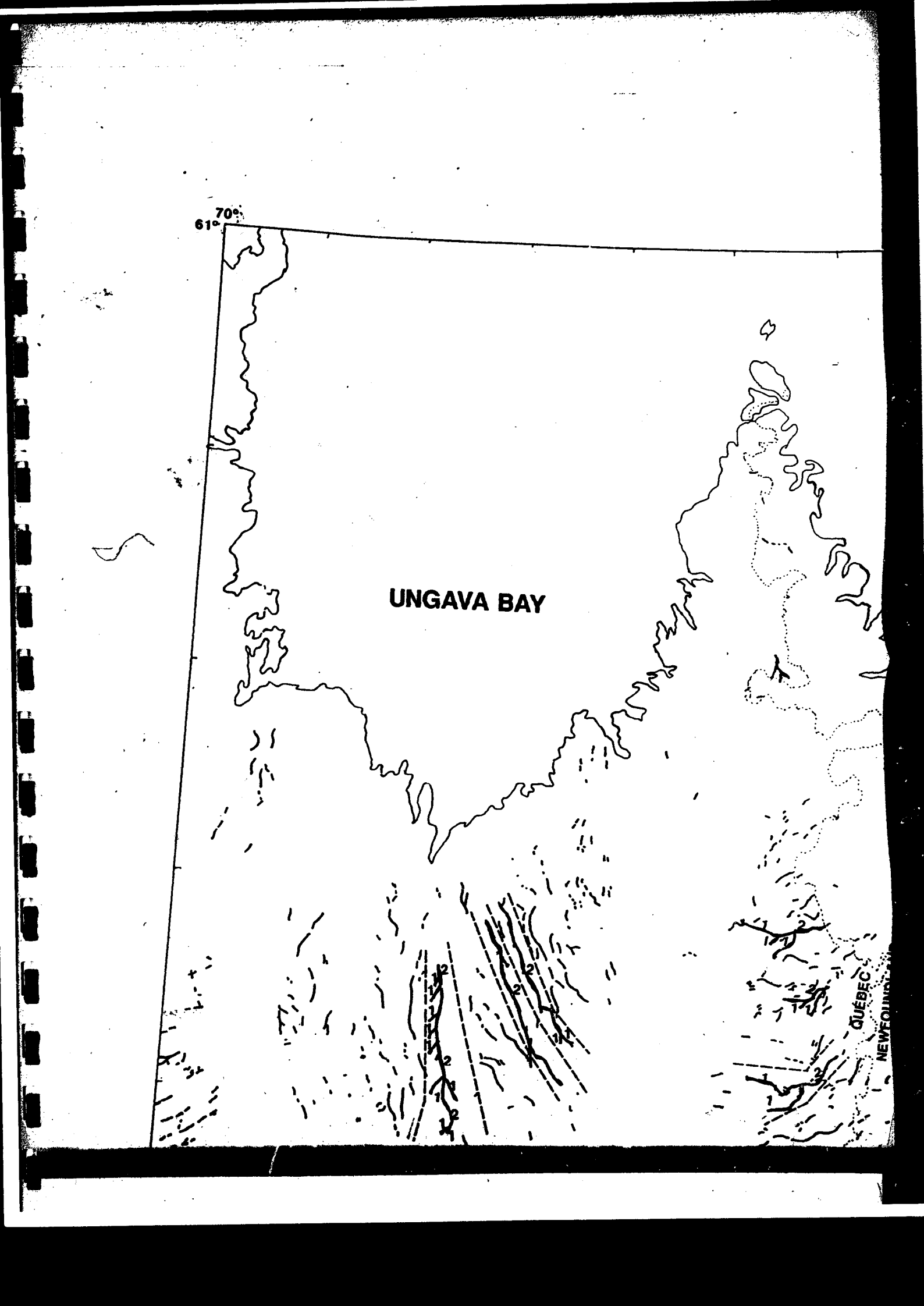
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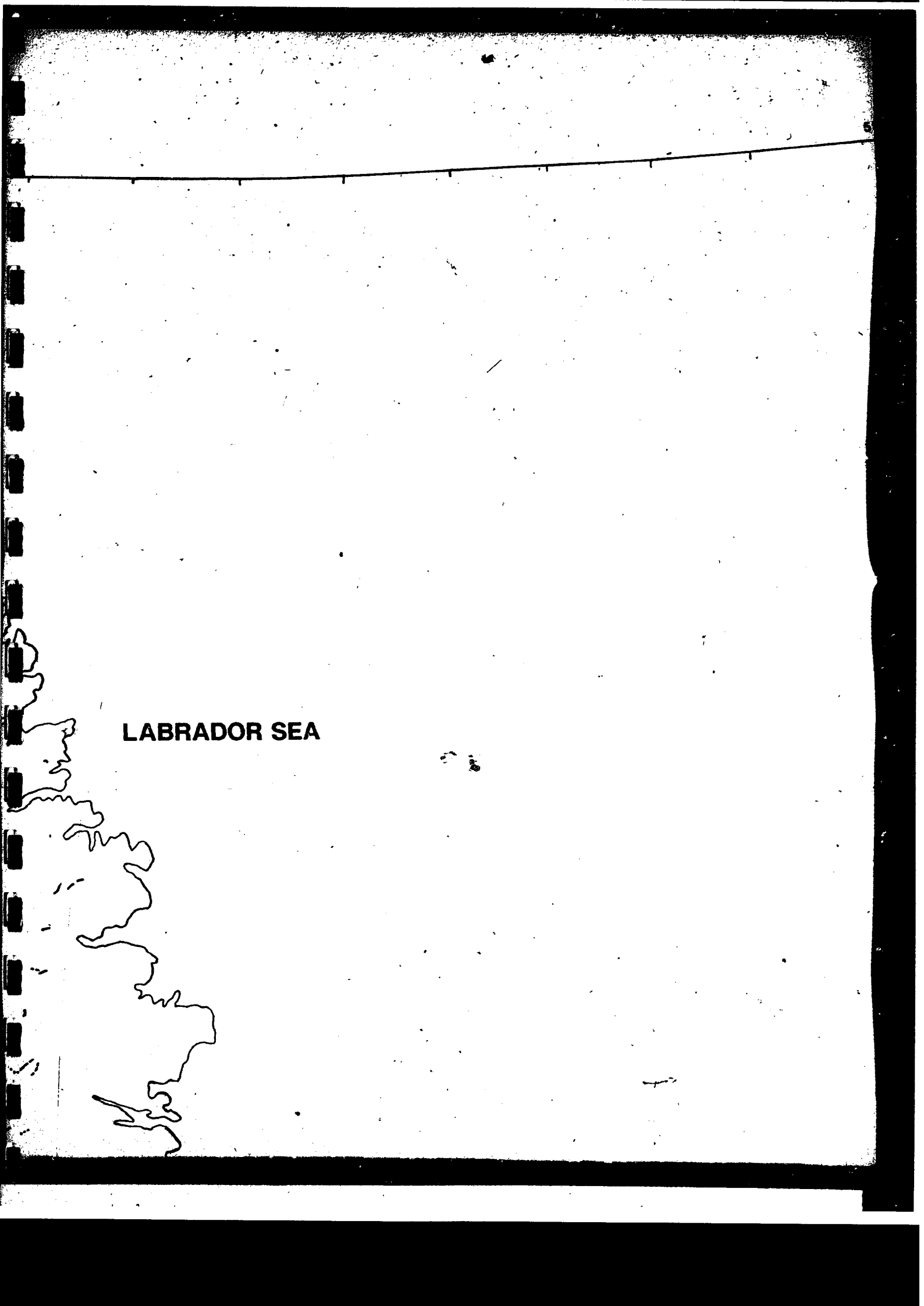
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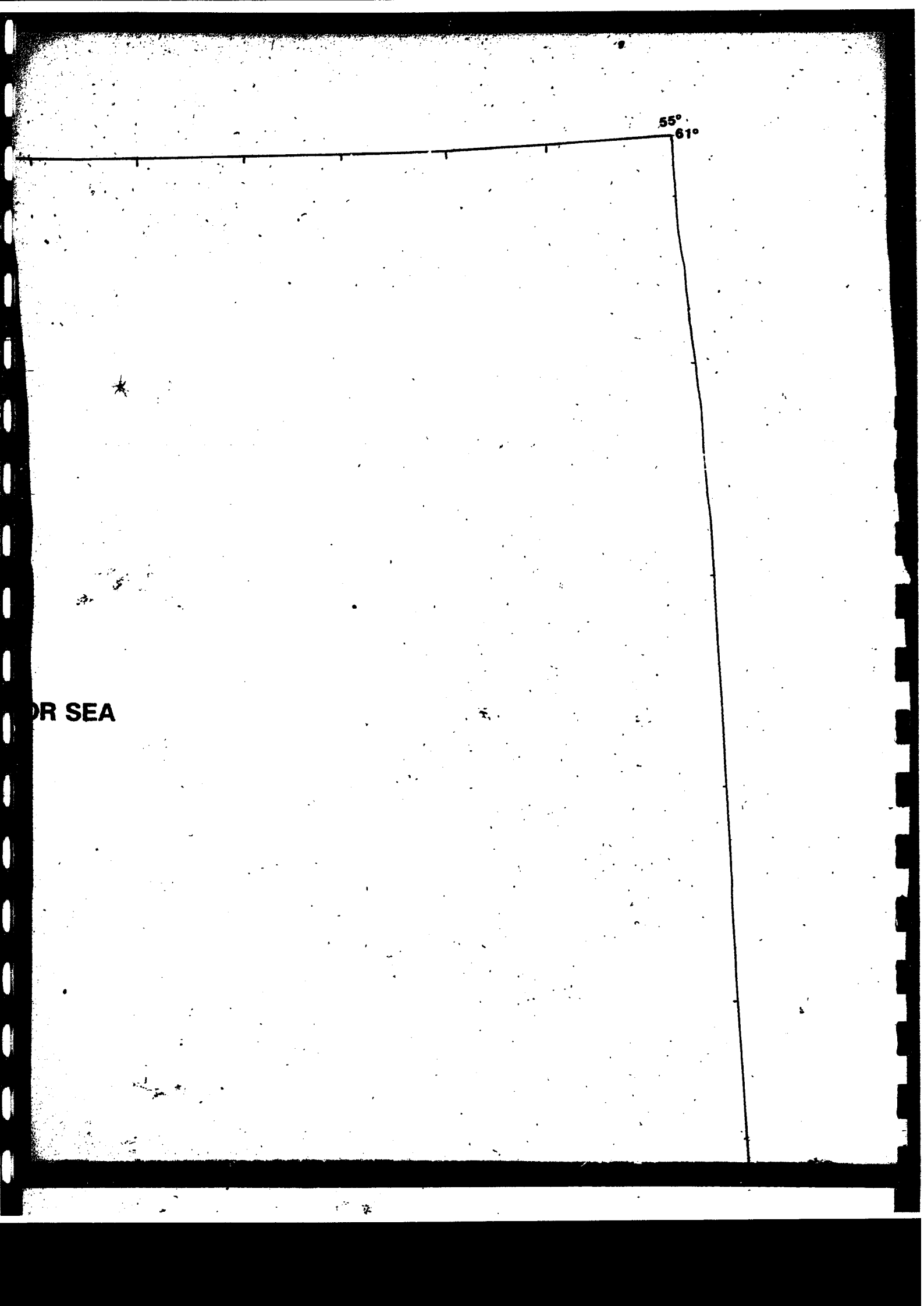

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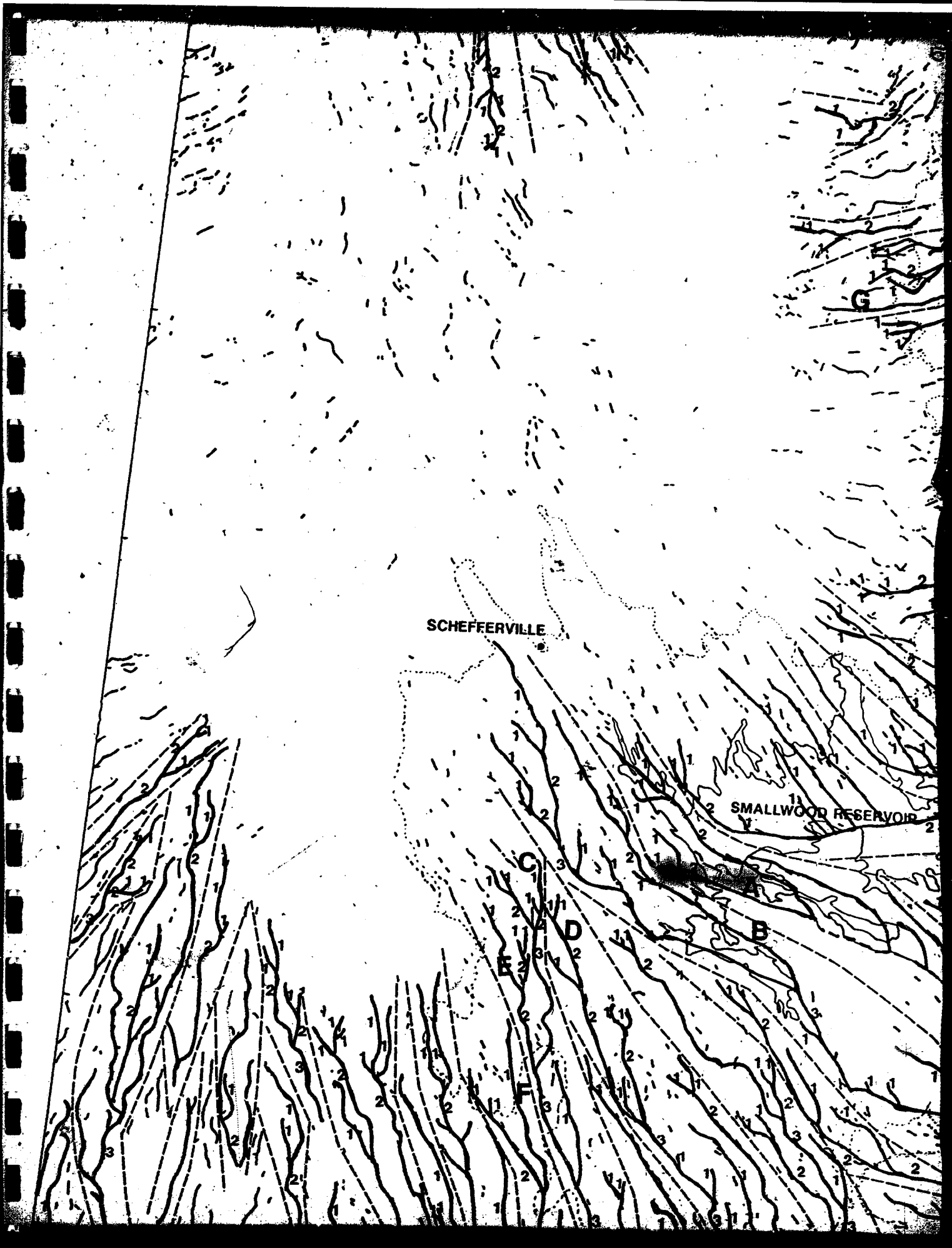
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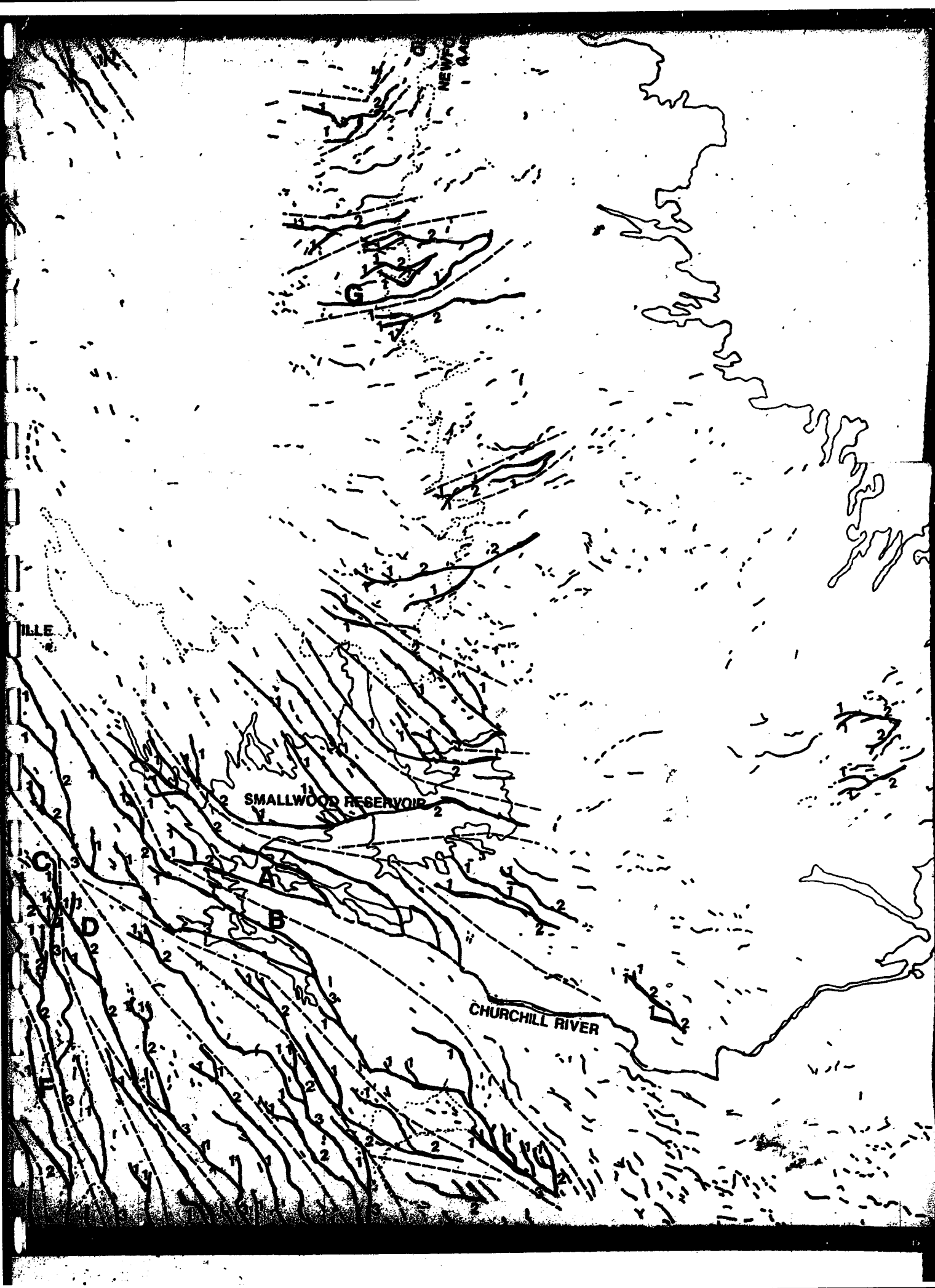
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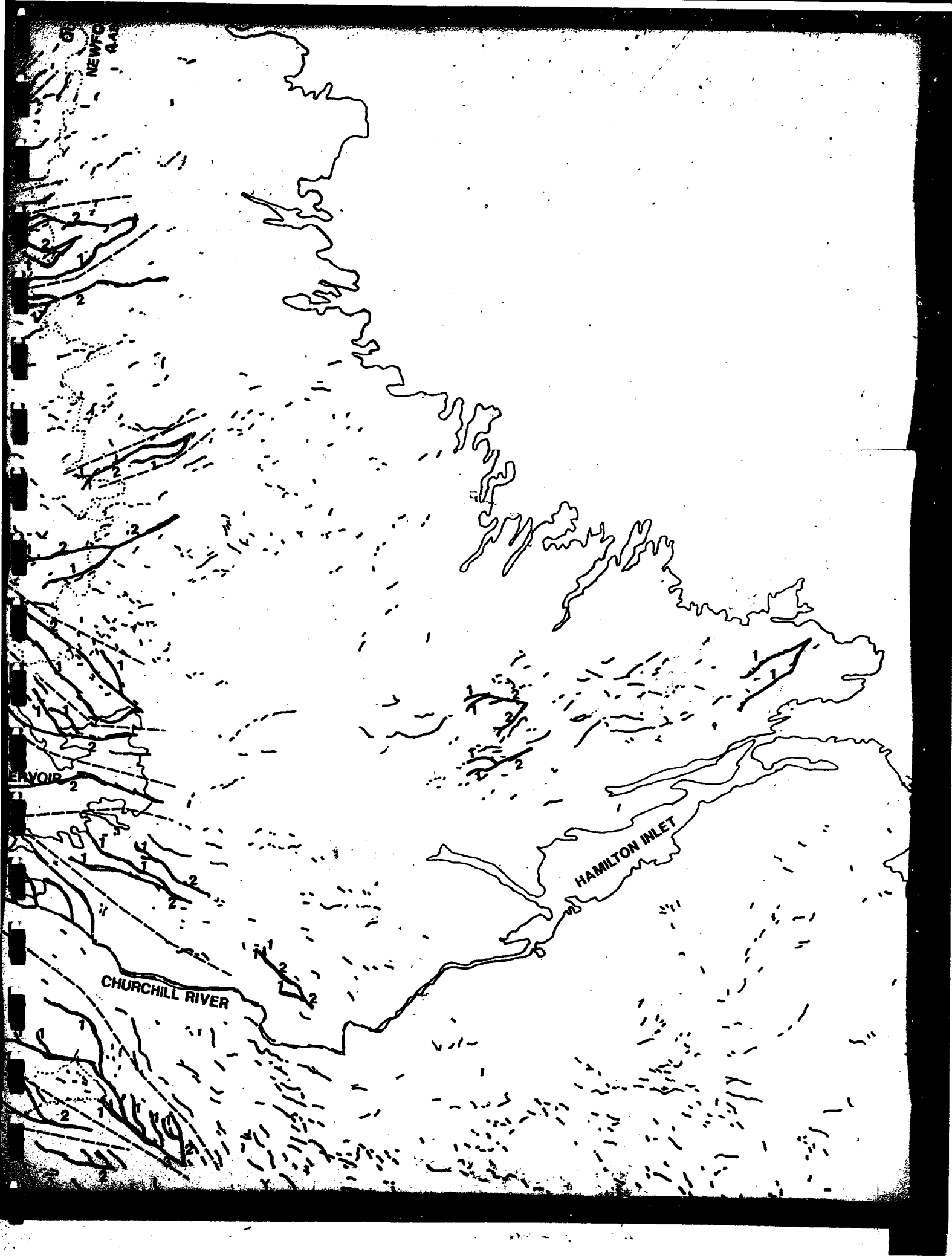
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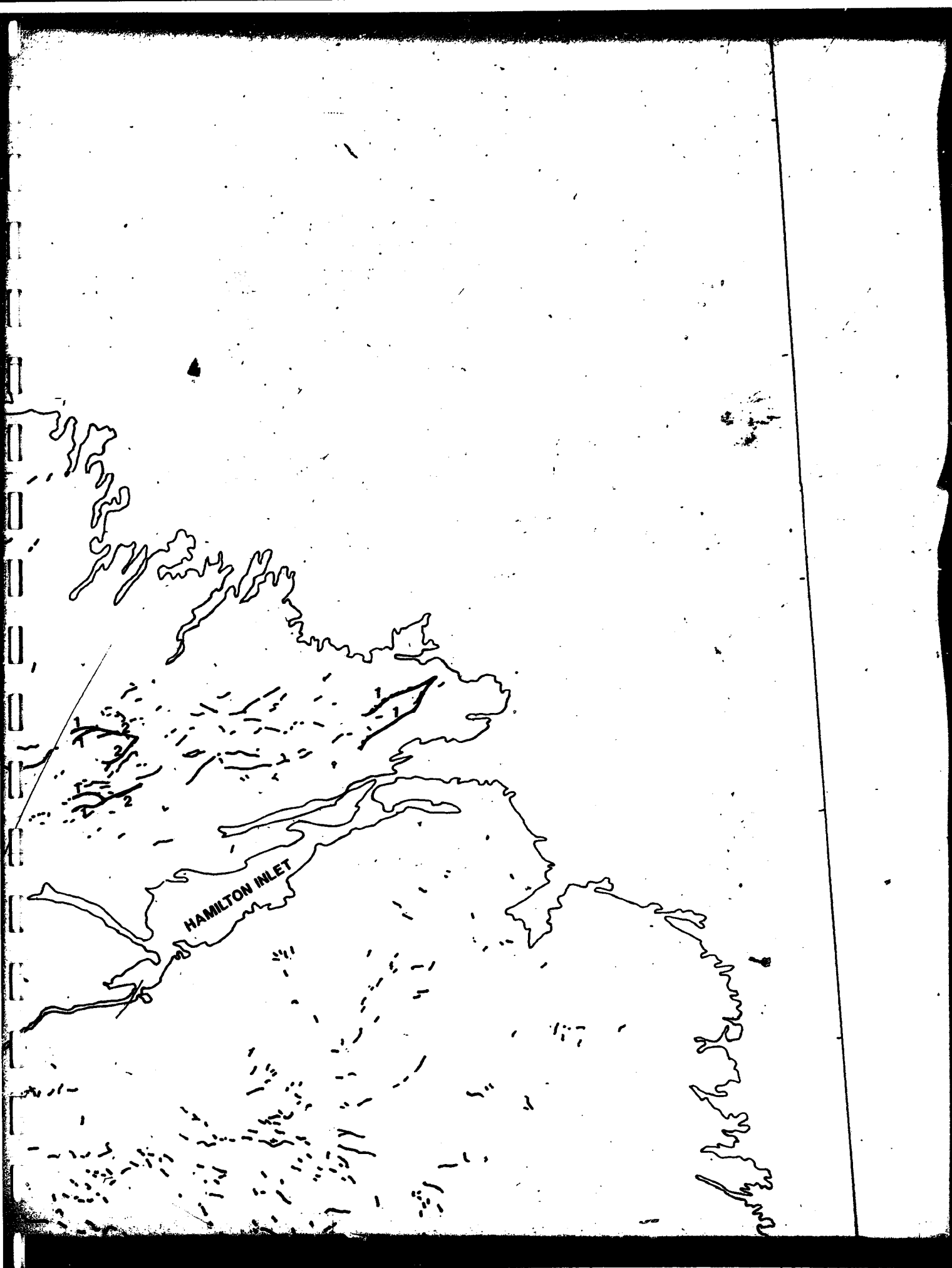

LABRADOR SEA


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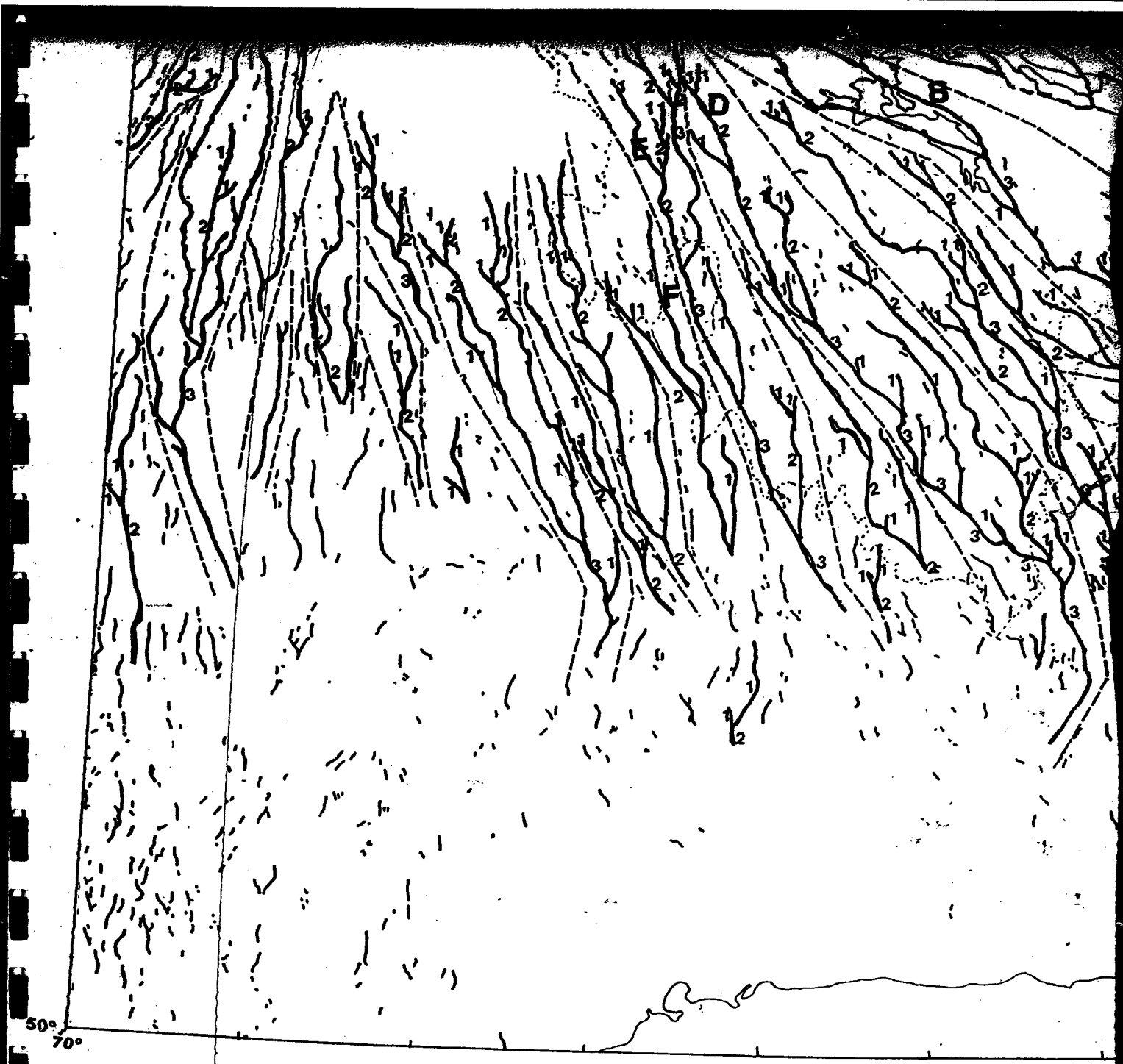
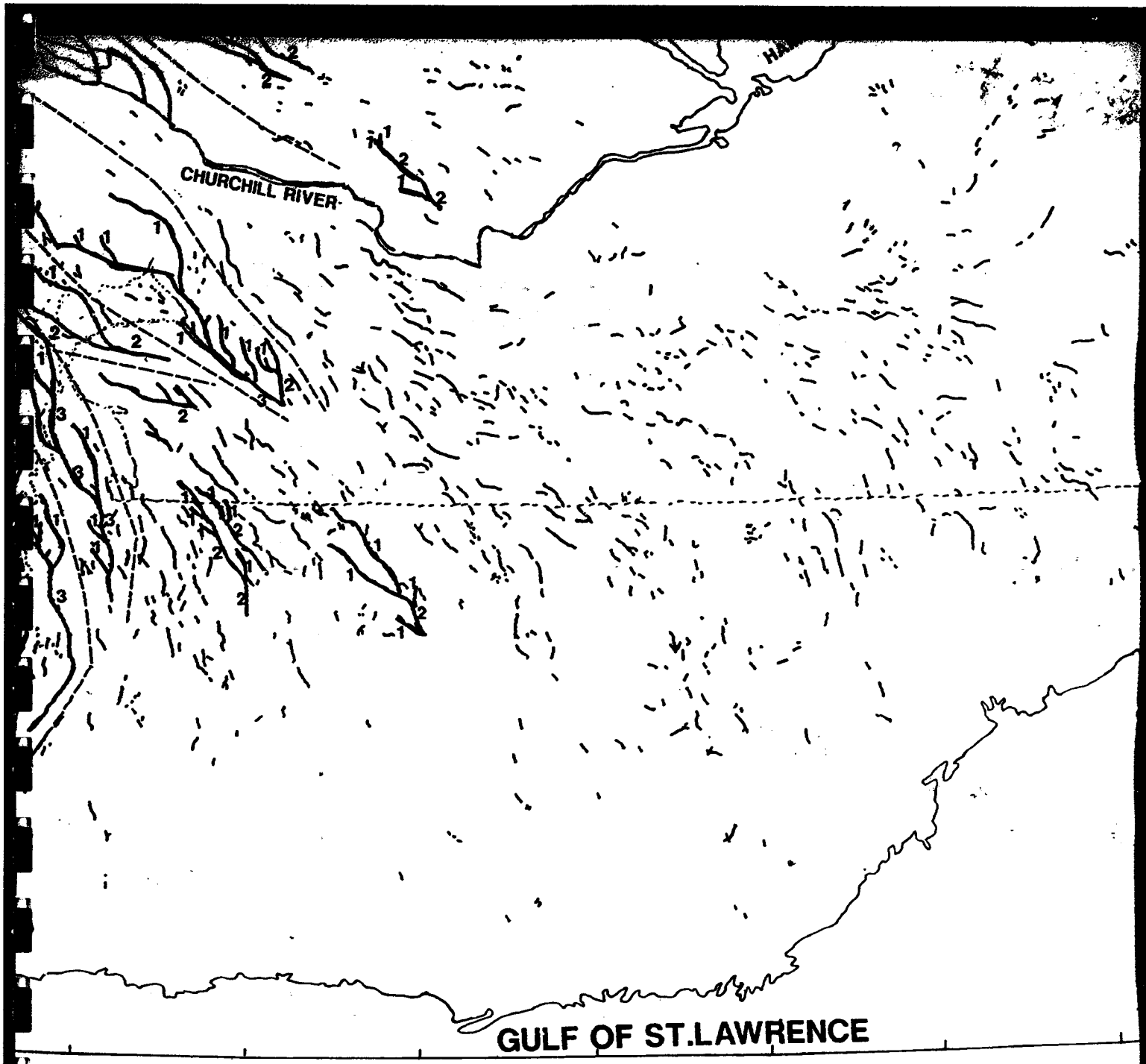


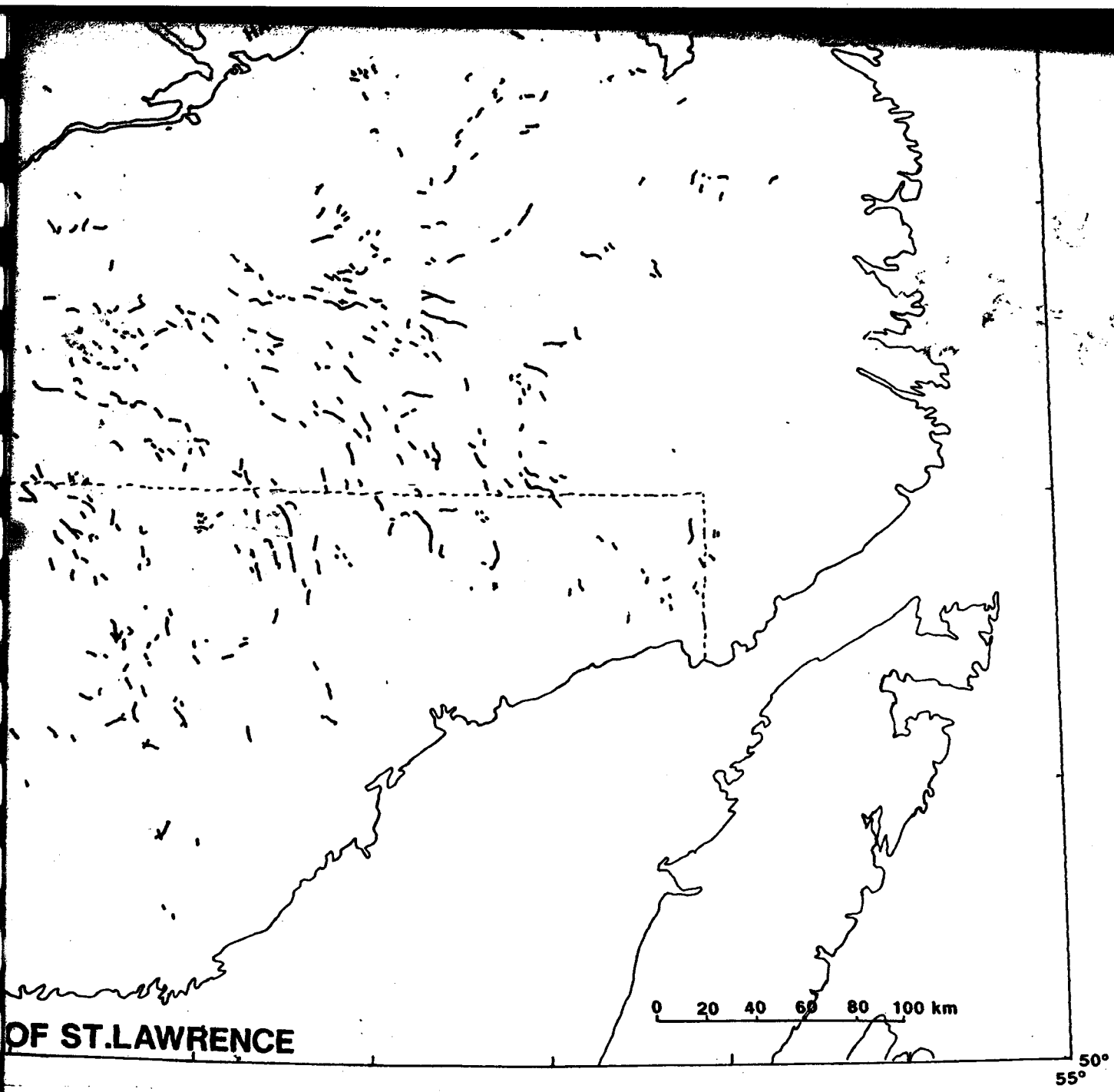
Plate 1. Distrib
basins of esker systems
(B), Shabogamo esker



Plate 1. Distribution of eskers in Labrador, with interpretation of probable connections between es
basins of esker systems (- - -), and Horton ordering of esker branches for those systems which display it.
(B), Shabogamo esker (C), Ashuanipi esker (D), De Mille esker (E), Moose Head esker (F), and Lac Bris



Distribution of eskers in Labrador, with interpretation of probable connections between esker segments (>), limits of drainage systems (- - -), and Horton ordering of esker branches for those systems which display it. Gabbro esker (A), Ossokmanuan esker (B), esker (C), Ashuanipi esker (D), De Mille esker (E), Moose Head esker (F), and Lac Brisson esker (G) are identified.



ons between esker segments ( ), limits of drainage
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, and Lac Brisson esker (G) are identified.

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