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Scales and rates of glacial sediment removal: a 20 km long, 300 m deep trench created beneath Breiðamerkurjökull during the Little Ice Age

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ABSTRACT. A 20 km long, 2–5 km wide trench, which extends to 300 m below sea level, is believed to have been created by removal of sediment during the advance of Breiðamerkurjökull in the Little Ice Age. Between 1732 and 1890, the glacier advanced by 9 km, covered an area of 45 km^2 and excavated a volume of $5 \times 10^9\ m^3$, equivalent to an average of 110 m over this area. Average sediment-removal rate during the 158 years was $32 \times 10^6\ m^3\ a^{-1}$ or $0.7\ m\ a^{-1}\ km^{-2}$ averaged over the area covered by the advancing glacier. Calculated over the whole drainage area of the eastern branch of the glacier of 750 km^2, the denudation rate would be $4 \times 10^{-2}\ m\ a^{-1}\ km^{-2}$. Fluvial processes are estimated to have carried about $30 \times 10^6\ m^3\ a^{-1}$, and the sediment fluxes within the ice and by the deforming subglacial till are estimated to be 10^5 and $10^6\ m^3\ a^{-1}$, respectively. The average sediment concentration in the glacial streams would have been about 10 $kg\ m^{-3}$. Such concentrations have been measured in Icelandic rivers during jökulhlaups and surges. Several surging events took place during the advance of Breiðamerkurjökull, and jökulhlaups drain regularly beneath the glacier from ice-dammed marginal lakes. The present rate of transport, although considerable, seems to be about $10 \times 10^6\ m^3\ a^{-1}$, of which 30% is transported by the river to the sea and 70% is dumped into a proglacial lake.

INTRODUCTION

Breiðamerkurjökull is located in the highly maritime climate of southeast Iceland and is one of the most active outlet glaciers of the ice cap Vatnajökull (Fig. 1). The outlet flows down to the coastal sandur delta Breiðamerkursandur, which is believed to be composed of a wedge of late-Weichselian and Holocene sediments (Boulton and others, 1982). Since the settlement of Iceland 1100 years ago, large glacier variations and major glacially induced changes in landscape have taken place in the Breiðamerkurjökull area. At the time of the settlement much land which is now largely covered by Breiðamerkurjökull was vegetated and occupied by several farms. During the cold period between the Middle Ages and the end of the last century (the Little Ice Age), the glacier outlet advanced maybe 10–15 km, devastating vegetation and ruining the farms. This advance and its consequences are well known and historically documented in medieval annals, county records, journals of churches, travel accounts and geographical maps (Henderson, 1818; Thienemann, 1824; Pálsson, 1883, 1945; Thoroddsen, 1892, 1905/06; Bárðarson, 1934; Thórarinsson, 1943, 1974; Nörlund, 1944; Sigurðsson, 1978). This saga is presented here.

During the retreat of the glacier in the 20th century, land has reappeared, revealing changes since the settlement (see Howarth and Price, 1969; Price, 1971, 1982). The most outstanding new feature is a large proglacial lake (Jökulsárlón) where there was farmland before the advance. This lake basin is considered to have been excavated by the advancing glacier, and bears witness to exceptionally high rates of sediment removal since about 1800 (Boulton and others, 1982).

New radio-echo soundings of the glacier itself show that ice is still hiding landforms created during the neoglacial advance. These changes in landscape give an even more spectacular insight into the landscaping power of the glacier: a 20 km long trench, 2–5 km wide, which is up to 300 m below sea level. We believe this trench to have been created by removal of sediment during the advance of the glacier during the Little Ice Age, i.e. after AD 1400.

This paper describes the evidence for this statement and discusses glacial, subglacial and fluvioglacial processes responsible for the excavation of the trench and the transport of sediment to the sea.

DESCRIPTION OF BREIÐAMERKURJÖKULL AND BREIÐAMERKURSANDUR

Breiðamerkurjökull (total area $A = 910\ km^2$, accumulation area $A_c = 500\ km^2$, ablation area $A_a = 410\ km^2$) is bounded to the west by the huge volcano Öræfajökull (2119 m a.s.l.), to the north by the nunataks Mávabyggðir and Esjufjöll and to the east by Veðurárdalsfjöll, all reaching elevations of more than 1300 m (Fig. 1). The northeastern part of the outlet drains from the ice dome Breiðabunga through a pass between Esjufjöll and

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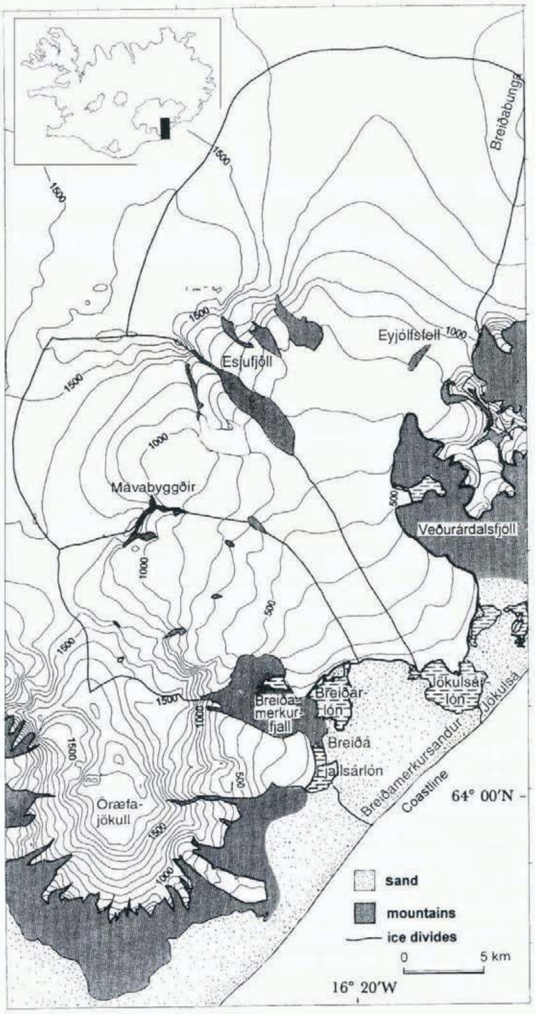

Fig. 1. Breiðamerkurjökull and surroundings. The outlet is divided into three branches by two medial moraines. Contour heights are given in metres above sea level.

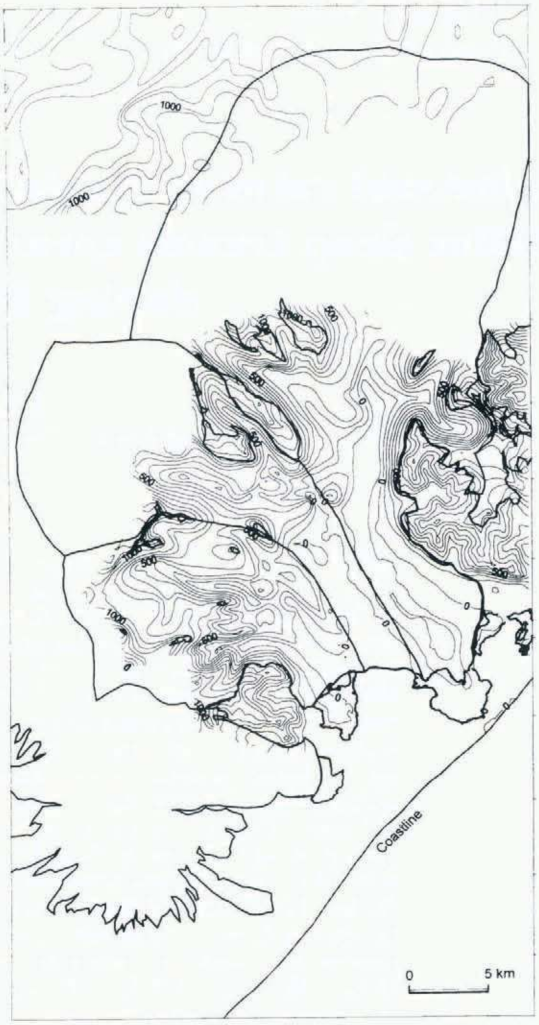

Fig. 2. The bedrock topography of Breiðamerkurjökull, surveyed by radio-echo soundings (Björnsson and others, 1992). Contours in metres.

Veðurárdalsfjöll. The present equilibrium line lies at an elevation of 1100 m. The climate is highly maritime with net mass balance of 4–7 m a^{-1} in the uppermost accumulation area and ablation of about 10 m a^{-1} at the terminus (50 m elevation) where the annual precipitation is about 2000 mm.

Breiðamerkurjökull can be divided into three lobes or branches which are separated by medial moraines that originate from the nunataks Mávabyggðir and Esjufjöll and related valley glacier (Figs 1–3).

Western branch

The western branch ($A = 160$ km^2, $A_c = 60$ km^2, $A_a = 100$ km^2, and 18 km measured along a central flowline) falls steeply from the northeastern slopes of Öræfajökull towards a calving front at the proglacial lake Breiðárlón (15 m a.s.l.). The river Breiðá flows from the lake. The branch is bounded to the north by the nunataks and the medial moraine of Mávabyggðir. The bed is irregular, showing signs of substantial valley erosion, and only beneath the outermost 4 km of the outlet does the bed form a sandur plain below 100 m elevation (Figs 2 and 3; Björnsson and others, 1992). Northeastwards from Breiðárlón a trench, 7 km long and up to 1 km wide, extends below sea level. Another depression below sea level is located 2 km north of Breiðárlón and does not reach the present glacier margin. An ice-dammed lake by Breiðamerkurfjall, drains beneath the western branch down to Breiðárlón (Fig. 1).

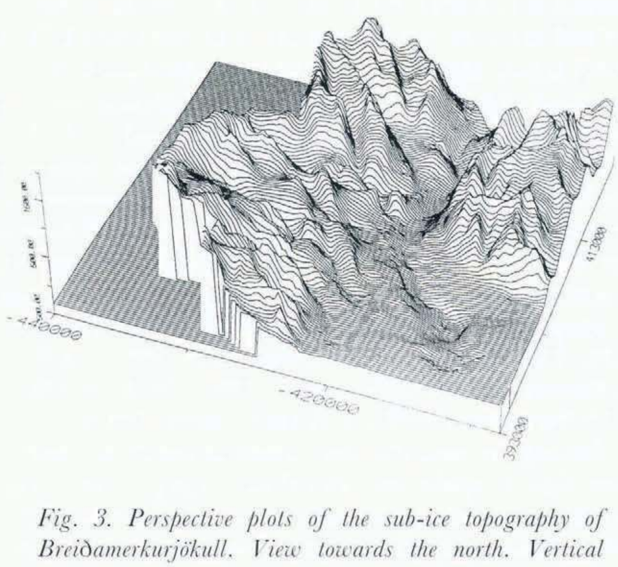

Fig. 3. Perspective plots of the sub-ice topography of Breiðamerkurjökull. View towards the north. Vertical exaggeration ten times horizontal.

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Central branch

The central branch ($A = 210$ km^2, $A_c = 100$ km^2, $A_a = 110$ km^2, and 26 km long) is bounded by the nunataks Mávabyggðir and Esjufjöll and their medial moraines. Most of the bed is formed of glacially sculptured mountains, but a 3 km wide plain below the 100 m contour stretches 10 km up-glacier beneath the tongue. No river drains from the front as the meltwater is drained towards the eastern branch.

Eastern branch

The eastern branch ($A = 540$ km^2, $A_c = 340$ km^2, $A_a = 200$ km^2) drains from Breiðabunga (1500 m a.s.l.), 34 km down to a calving front at the proglacial lake Jökulsárlón. The accumulation area is situated in the central part of Vatnajökull where the glacier bed is above 500 m a.s.l., from where the ice flows steeply down to a low-lying ablation area. About half of the bed in the ablation area is below 100 m, and this contour extends 25 km up-glacier from the front (Figs 2 and 3). We suggest from this sub-ice information that a sandur field (a sediment wedge), reaching to the nunataks Esjufjöll and the central highland northeast of Esjufjöll, was formed in postglacial times (Boulton and others, 1982). The present glacier bed in this area, however, slopes rapidly down and forms a trench which extends below sea level over a distance of 20 km down to Jökulsárlón. The maximum depth of this trench is 300 m below sea level, 2–3 km up-glacier from Jökulsárlón where the ice is 300–400 m thick.

The area exposed from beneath the retreating glacier since the Little Ice Age consists of a consolidated mixture of till and sand. Seismic refraction on Breiðamerkursandur near the snout of the glacier (Bogadóttir and others, 1986) and reflection profiles in the lake Jökulsárlón (Boulton and others, 1982) suggest that the margin of the glacier and the foreland are underlain by glacial drift. In the coastal area the bedrock is overlain by moraines (40 m thick) and topped by sand. In front of the lake Jökulsárlón the depth down to the bedrock is 130–140 m, and the maximum depth of the present lake is 190 m. In other parts of Breiðamerkursandur the depth to the bedrock is 30–80 m. The trench is located in a glacially eroded bedrock valley which extends as Breiðamerkurdjúp southeast of the river mouth of Jökulsá, 60 km to the edge of the continental edge (see Boulton and others, 1982, 1989). We suggest that the trench beneath the glacier may reach down to bedrock in the deepest parts, but the sides of the trench consist of unconsolidated sediments.

Hydrology

Water drains to the proglacial lake Jökulsárlón from a basal drainage area of 750 km^2. The glacier receives enormous amounts of water through rainfall. Maximum rainfall intensity recorded is 230 mm in 24 h at the margin. Surface runoff flows into moulins down to the glacier base in the lower three-quarters of the ablation area. The river Jökulsá flows from the lake Jökulsárlón. The mean annual discharge from the glacier to the river Jökulsá is 130 m^3 s^{-1}, but daily peak values of 750 m^3 s^{-1} have been recorded. The flow of water from the glacier reaches its highest levels between July and mid-September. Discharge may fluctuate rapidly and jökulhlaups are frequent from two lakes which are dammed at the eastern margin of Breiðamerkurjökull.

Only small amounts of supraglacial debris are found on the glacier, and nearly all the sediment supplied to the streams appears to be derived from subglacial drift. Most of the sediment load is presently dumped into the lake. Typically, suspended-sediment loads carried by the river Jökulsá are 1.5 kg m^{-3} (Rist, 1957; personal communication from L. S. Zóphóníasson, 1995). Data on bedload are not available.

CHANGES OF BREIÐAMERKURJÖKULL AND BREIÐAMERKURSANDUR IN HISTORICAL TIMES

Changes of glaciers

During the climatically mild period of the settlement of Iceland (AD 874–930) and for several centuries thereafter, the glacier outlets of Vatnajökull were substantially shorter than they have been for the last three to four centuries (see Thórarinsson, 1943). Tómasson and Vilmundardóttir (1967) believe that the outlet glaciers of Vatnajökull may have been up to 20 km further back at the time of the settlement than they now are. The land adjacent to and now covered by Breiðamerkurjökull was settled and occupied by farms and covered with vegetation. At that time several valley glaciers may have flowed down to Breiðamerkursandur, but most of the flat area below the 100 m contour of the bed would have been free of ice. In that case, no ice-dammed lake would have existed in Veðurárdalur, nor would a lake be dammed in Breiðamerkurfjall (Fig. 1).

A climatic deterioration set in during the 12th century. From about 1300 to 1900 the climate was cold, especially after 1600 which was presumably the coldest period in postglacial times. Eythórsson (see Ahlmann, 1953, p. 31) estimated that the firn line on southern Vatnajökull declined from about 1100 m around AD 1000–1100 to about 750 m elevation by 1650. This caused glacier advance which gradually destroyed the farming area. Prosperous farms were still reported in 1343 (Bárðarson, 1934, p. 28), but the glacier started to advance after AD 1400, with accelerating pace in the 17th century until Breiðamerkurjökull reached its post-glacial maximum in the 1890s. Two farms, Fjall and Breiðá, on the western side of Breiðamerkursandur were abandoned in the 1690s and shortly after AD 1700, respectively, because the glacier advanced over the pastures near the farm houses. On the eastern side the farm Brennhólar was overrun by ice in 1753, and Fell, which was protected by a large moraine, was destroyed in 1865 when the moraine was breached by the glacier (Thoroddsen, 1892, 1905/06).

The variations of the eastern branch of Breiðamerkurjökull, by the present river outlet of Jökulsá, are summarized in Figure 4. Altogether the glacier advanced by 9 km between 1730 and 1890. Several rapid advances have been described, which are

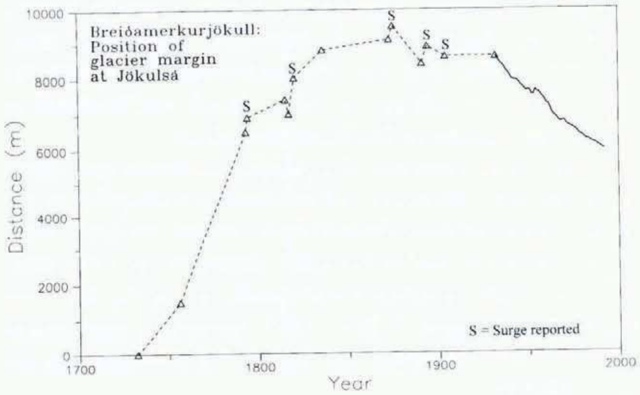

Fig. 4. Changes in the position of the front of Breiðamerkurjökull at the Jökulsá river (with reference to the position in 1735).

definitely surges. In 1794, the eastern part of Breiðamerkurjökull advanced 400 m between Whitsun and August, according to Pálsson (1945, p. 358). During 1820 the glacier advanced by 1 km (in some days by 4–8 m) according to Thienemann (1824), while large masses of water poured from underneath the glacier, which started to retreat shortly afterwards. Inhabitants told Thienemann that such rapid advances occurred approximately every fifth year, followed by recession. During the period 1794–1820 alternating rapid advances and slow recessions took place (Thórarinsson, 1943). In 1869 an advance similar to that of 1820 took place and the glacier almost reached the sea (Norðanfari, 1870). In 1875 a rapid advance was reported and the inhabitants feared the glacier would reach the sea (Watts, 1876). The last advance of this nature was reported in the early years of this century (personal communication from S. Björnsson, 1995).

Changes in the sandur field

Large landscape changes have taken place on Breiðamerkursandur during historical times in association with the glacier variations. The area has changed from a vegetated area (called Breiðamörk) to a glacial sandur area. The presence of large lakes, like the ones found in the present proglacial area, is neither mentioned in written records nor shown on maps (Pálsson, 1883, 1945; Thoroddsen, 1892, 1905/06; Thórarinsson, 1943; see Nörlund (1944) and Sigurðsson (1978) for information about the maps of Knoff (from 1732), Pálsson (from 1794), Gunnlaugsson (from 1834) and the Danish Geodetic Survey (from 1903/04)). Therefore we conclude that the trench was excavated during the glacier advance of the Little Ice Age.

The volume of the proglacial moraines which were piled up is a negligible proportion of the volume removed from the glacier bed when the trench was formed. The volume of the moraines is only of the order of 15×10^6 m^3. (15 m high, 200 m in the down-glacier direction and about 5 km wide across the front of the trench). Assuming, conservatively, the present porosity of 0.2 for this deposited material and 0.4 for deformable till beneath the glacier, the moraines account for about 20×10^6 m^3 (0.4%) of the volume removed from the trench. The main part of the excavated material was transported by proglacial rivers to the sea, building an outwash fan beyond the mouth of the river Jökulsá. From 1817 to 1904 the coastline moved seawards by 1100 m due to accumulation of sediments from the glacier in excess of what the littoral currents were able to carry away (Fig. 5).

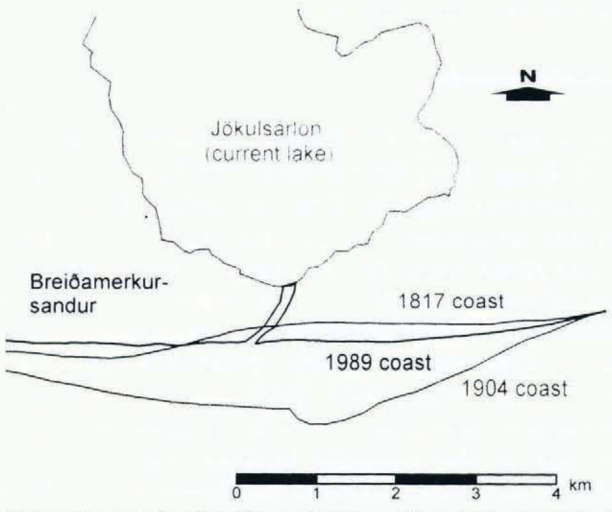

Fig. 5. Changes in the position of the coastline at Breiðamerkursandur according to maps of 1817 (the same as on Gunnlaugsson map of 1834; see Sigurðsson, 1978), 1904 (Danish Geodetic Survey) and 1989 (Icelandic Geodetic Survey).

The river Jökulsá (meaning glacial river), first mentioned in the Land Intake Book, became gradually shorter as the glacier advanced, in spite of the seaward movement of the coastline.

The proglacial lake Jökulsárlón, first visible in 1932, has expanded during continous retreat of the glacier. In 1975 a bathymetric survey of the lake was undertaken. The lake area was 7.9 km^2 and the estimated volume was 500×10^6 m^3 (Boulton and others, 1982). In 1991 its area was 10.4 km^2.

Since the formation of Jökulsárlón in the 1930s, the shore off the river outlet has been retreating because the sediment load from the glacier has been largely dumped into the lake, and only a small amount added to the coast by the river. Comparison of maps from 1904 and 1989 shows that the coastline has retreated over a distance of 4 km on both sides of the river outlet (Fig. 5). The maximum shoreline erosion has been 700 m in 85 years, an average of 8.5 m a^{-1}. The retreat from 1945 to 1989 was similar (Víkingsson, 1991; Jóhannesson, 1994).

REMOVAL OF SEDIMENT BENEATH BREIÐAMERKURJÖKULL

Sediment-removal rates

The discovery of the trench beneath the eastern branch of Breiðamerkurjökull and information on the glacier advance make it possible to evaluate rates of excavation and transport of sediments from beneath that glacier during the Little Ice Age. We assume that before the glacier advance the surface of the sandur field where the trench is now located had a slope similar to that of the surroundings of the present trench.

During the period 1732–1890, the glacier advanced by 9 km, covered an area of 45 km^2 and excavated a volume of 5×10^9 m^3 or 110 m averaged over this area. A uniform sediment-removal rate during the glacier advance of 158 years was 32×10^6 m^3 a^{-1} or 0.7 m a^{-1} km^{-2} averaged over the area covered by the advancing glacier. Calculated over the whole drainage area of the eastern branch of 750 km^2, the denudation rate would be 4×10^{-2} m a^{-1} km^{-2}. These removal rates are exceptionally high by any standard. Similar calculations for other time-spans are given in Table 1, assuming that the advancing glacier pushed forward and replaced the whole volume of the respective part of the trench (Fig. 6). For the shorter time-spans this assumption is questionable. The lowest estimate for the removal rate is obtained if we assume the whole 20 km long trench was excavated during 800 years, after the settlement of Iceland.

Table 1. Estimated maximum rates of sediment transport from the eastern branch of Breiðamerkurjökull

Period	*Advance of glacier*			*Volume of trench*	*Transport rate*	*Denudation rate*
	a	km	km^2	10^6 m^3	10^6 m^3 a^{-1}	m a^{-1}
1732–1890	158	9	45	5000	32	0.7
1732–1765	33	1.5	7	800?	24?	3.5?
1765–1794	29	5	23	3300?	114?	4.9?
1100–1900	800	20	80	11 500	14	0.18
1794–1965	171			500	3	0.37*
1794–1932	138			500	2.8	0.35*

* From Boulton and others (1982).

Boulton and others (1982) concluded that the basin of the proglacial lake Jökulsárlón was created when Breiðamerkurjökull advanced over Breiðamerkursandur in the 18th and 19th centuries. Hence, the volume of 500×10^6 m^3 of sediments was excavated in 130–175 years at most. This is equivalent to a layer of 64 m being removed, averaged over the whole lake area, at a minimum rate of 0.37 m a^{-1}. Thus, the average sediment load of the river must have been 3 to 4×10^6 m^3 a^{-1}.

Sediment-flux relations

Having derived estimates for the total removal rates we can now discuss the various modes of sediment transport by the advancing glacier during the excavation of the trench. The sediment flux, Q_t, through a cross-section of width W perpendicular to the direction of ice flow, is the sum of the flux carried within the ice, Q_i, the flux due to deformation of a subglacial till layer, Q_s, and the flux carried by subglacial streams, Q_w:

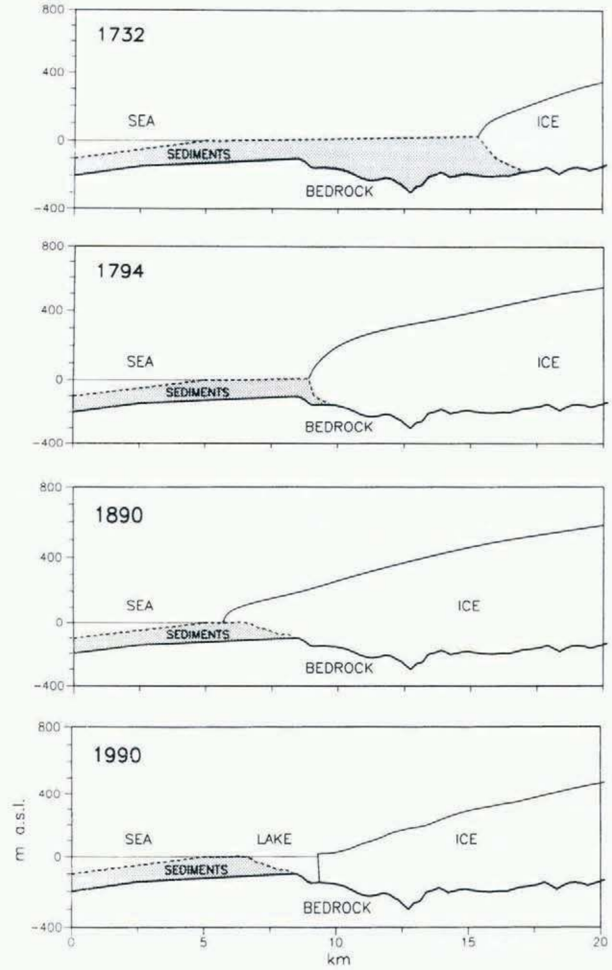

Fig. 6. Schematic sections along a central flowline of the eastern branch of Breiðamerkurjökull at particular times between 1730 and 1990.

$$Q_t = Q_i + Q_s + Q_w\,.$$

The debris flux in the ice is $Q_i = C_i W h_b u_b$ where u_b is the average velocity of the basal ice, W is the width of the glacier, h_b is the thickness of the layer of sediment-laden ice and C_i is the concentration of debris given as mass per volume of ice. The sediment concentration is mainly in the basal ice, and flux in the supraglacial and englacial ice facies can be neglected here. Considering the eastern branch of Breiðamerkurjökull, we can estimate $Q_i = 10^5$ m^3 a^{-1}, assuming a sediment concentration of 10% per volume in a basal layer of $h_b = 1$ m, $W = 4$ km, and $u_b = 200$ m a^{-1} (assuming plug flow of which velocity was estimated from aerial photographs).

The flux carried by the deforming subglacial till is $Q_s = W h_s u_s$ where h_s is the thickness of the deforming subglacial till layer and u_s is the average speed of the till layer. This flux is roughly estimated to be of the order of 10^6 m^3 a^{-1}, assuming $h_t = 2$ m, a linear velocity profile in the deforming layer (Alley, 1991), and that the ice is fully coupled to and not sliding over the till.

The sediment flux in the subglacial streams is $Q_w = C_w q_w$ where C_w is the concentration of sediments in the water and q_w is the discharge of water drained along the glacier bed. This transport by fluvial processes during the excavation of the trench must have been several factors higher than the other transport processes: during the period 1732–1890 about $30 \times 10^6 m^3 a^{-1}$ of sediments (Table 1). The present rate of transport, however, seems to be about one-third of this; about $10 \times 10^6 m^3 a^{-1}$, of which 30% are transported by the river to the sea ($q_w = 130 m^3 s^{-1}$, $C_w = 1.5 kg m^{-3}$, density $2000 kg m^{-3}$) and 70% are dumped into the lake. The accumulation of sediments in the lake over the period 1932–75 was obtained from the interpretation of lake-sediment stratigraphy by Boulton and others (1982, p. 43).

During the excavation period 1730–1890, the average sediment concentration of a river of the same discharge as Jökulsá ($130 m^3 s^{-1}$) would have been about $10 kg m^{-3}$. Such concentrations have been measured in Icelandic rivers during jökulhlaups and surges (Björnsson, 1979). The marginal ice-dammed lakes east of the glacier drained annually. During the Little Ice Age the ice dams were thicker than now, and the discharge of the jökulhlaups and their capacity to remove basal sediments would have been much larger than today. Further, several surging events took place during the advance of Breiðamerkurjökull, but this activity terminated early in the 20th century. Reduced sediment transport would also be expected now if the soft sediments have already been scoured away and the glacier is moving over hard bedrock in the deepest part of the trench. The possibility remains that depletion of soft sediments may have terminated the surge activity.

CONCLUSIONS

A 20 km long, 2–5 km wide trench, which is up to 300 m below sea level is believed to have been created by removal of sediment during the advance of Breiðamerkurjökull in the Little Ice Age, i.e. from AD 1400 to the 1890s. During the period 1730–1890 the glacier advanced by 9 km, and a volume of $5 \times 10^9 m^3$ was excavated, implying an average denudation rate of $0.7 m a^{-1}$ and a transport rate out of the trench of $32 \times 10^6 m^3 a^{-1}$. The sediment flux carried within the ice and by the deforming subglacial till may have been about 10^5 and $10^6 m^3 a^{-1}$, respectively. Thus, the transport by fluvial processes during the excavation of the trench must have been an order of magnitude higher than the other transport processes together, about $30 \times 10^6 m^3 a^{-1}$ of sediment. The present rate of transport, however considerable, seems to be about $10 \times 10^6 m^3 a^{-1}$, of which 30% is transported by the river to the sea and 70% dumped into the lake. Hence, fluvial processes carrying sediment loads three times greater than at present operated during the excavation of the trench. Then the average sediment concentration of a river of the same size as Jökulsá (130 $m^3 s^{-1}$) would have been about $10 kg m^{-3}$. Concentrations of that magnitude have been measured only in Icelandic rivers during jökulhlaups and surges. Such activities were frequent during the excavation of the trench beneath the eastern branch of Breiðamerkurjökull.

When glaciers are overriding layers of fine-grained sediments which are easily erodible by water, the supply and distribution of water may be the only limitation on the capacity for removal of subglacial sediments. At Breiðamerkurjökull the supply of meltwater and rain is great, and marginal lakes frequently drain in jökulhlaups. Water gets easily down to the base where it normally drains rapidly down the trench and during surges repeatedly makes contact with new basal sediments.

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