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Modern Glacial Landscapes

Icelandic Analogues for British Quaternary Environments

BGS Training Course Handbook

Internal Report IR/05/161

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Modern Glacial Landscapes

Icelandic Analogues for British Quaternary Environments

Tom Bradwell and Jeremy D Everest

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MODERN GLACIAL LANDSCAPES

Icelandic Analogues for British Quaternary Environments

MODERN GLACIAL LANDSCAPES

Icelandic Analogues for British Quaternary Environments

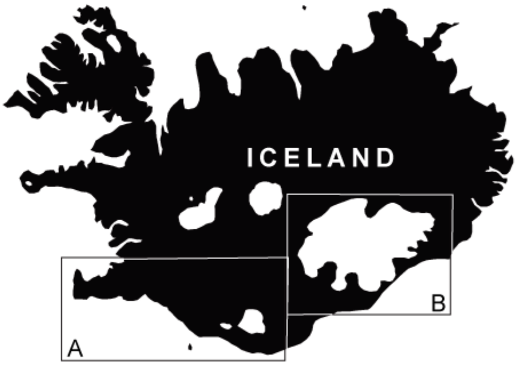
A BGS training course written and led by

Dr Tom Bradwell and Dr Jeremy Everest

CONTENTS

Each teaching unit is introduced with a general overview of the geographical site and the study topic. Specific aims are outlined as well as 3 research questions. Each unit is also supported by references and a datasheet outlining the main research undertaken to date.

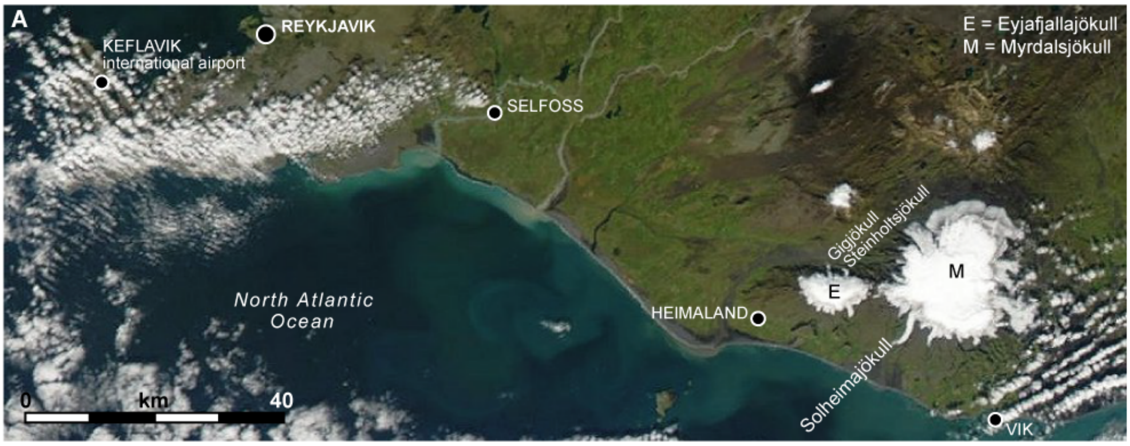
LOCATION MAP *Routeplanner and Glacier checklist*



Routeplanner and lodgings

Day 1: Keflavik --> Reykjavik --> Selfoss --> Heimaland
Day 2: Heimaland
Day 3: Heimaland
Day 4: Heimaland --> Vik --> KBK --> Svinafell
Day 5: Svinafell
Day 6: Svinafell
Day 7: Svinafell
Day 8: Svinafell --> Jokulsarlon --> Flatey
Day 9: Flatey
Day 10: Flatey
Day 11: Flatey
Day 12: Flatey --> KBK --> Selfoss --> Reykjavik

Glaciers of Eyjafjallajökull and Myrdalsjökull will be visited on Days 2-4. Vatnajökull glaciers will be visited on Days 4-11 (weather permitting).



UNIT 1: GIGJÖKULL
Glacier dynamics

UNIT 1: GIGJÖKULL *Glacier dynamics*

Gigjökull is a northward flowing outlet glacier of the Eyjafjallajökull ice cap in southern Iceland. The ice cap covers the summit of the Eyjafjöll massif, an active central volcano that last erupted in AD 1821-23. However, the volcano showed seismic signs of activity in the summers of 2001-2002. Eyjafjöll is part of the Eastern Volcanic Zone that also includes the volcanoes of Heimay, Katla, the Laki fissure, and Bardabunga. Gigjökull flows directly from the summit crater of the volcano, hence its name – *Gig* meaning 'crater' in Icelandic. In its accumulation area, within the crater, the ice is 1-200 m thick (Strachan, 2002). The glacier falls steeply, via a series of icefalls, from the crater rim to the foot of the mountain. Airfall tephra from the eruption of Hekla in 1947 covered much of the ablation area in black ash. The ice-front advanced rapidly in the years 1948-1954, possibly due to the heat-shielding effects of the tephra (Kirkbride & Dugmore, 2003). In stark contrast, the main trunk of the glacier has thinned rapidly in the last 10 years. Bedrock is now exposed at 250 m asl, where ice flowed as recently as 1998. The large moraine ramparts are a striking feature of this commonly visited glacier.

The **aims** of this unit are:

1. to introduce the concept of glaciers as a dynamic geological system.
2. to demonstrate how glaciers accumulate, waste and flow.
3. to understand the concepts of glacial erosion and deposition.

Research questions:

1. What are the key erosion processes and their relative effectiveness at the glacier sole?
2. How effective is the glacier as a sediment conveyor? How can we explain the size of the latero-frontal moraine complex?
3. To what extent are the fluctuations of the glacier governed by volcanic effects (ie. geothermal heating, tephra cover) rather than climate change?

References:

Bennett, M.R. & Glasser, N.F. 1996. *Glacial Geology: Ice sheets and Landforms*. John Wiley, Chichester, 364pp.

Kirkbride, M.P. & Dugmore, A.J. 2003. Glaciological response to distal tephra fallout from the 1947 eruption of Hekla, south Iceland. *Journal of Glaciology*, **49**: 420-428.

Ostrem, G. 1964. Ice melting under a thin layer of moraine and the existence of ice in moraine ridges. *Geografiska Annaler*, **41**: 228-230.

Strachan, S. 2002. *Ice-radar investigations on Eyjafjallajökull, Iceland*. Unpublished PhD thesis, University of Edinburgh.

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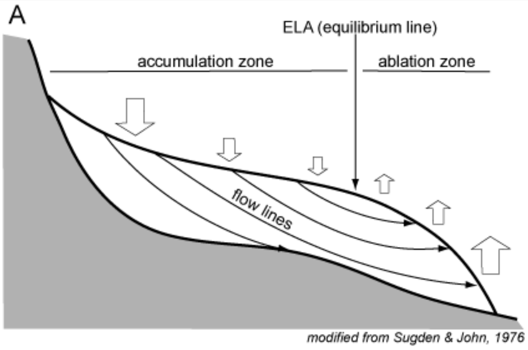
UNIT 1: GIGJÖKULL *Glacier dynamics*

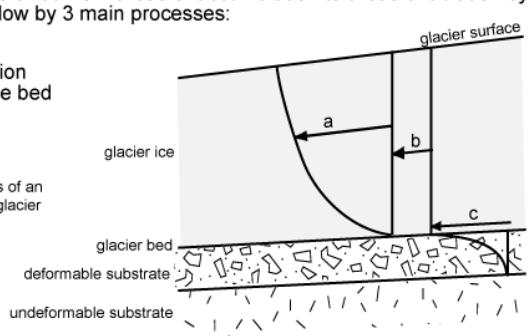
A



Snow and ice are transferred from areas of accumulation to areas of ablation by glacier flow. Glaciers flow by 3 main processes:

a. Basal sliding
b. Internal deformation
c. Deformation of the bed

(right) Typical flow dynamics of an Icelandic (ie. warm-based) glacier



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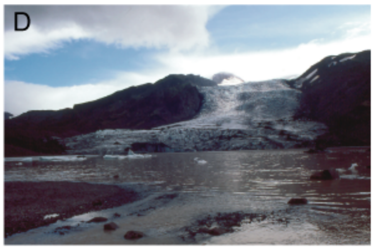
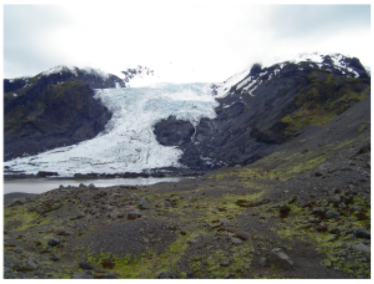
D



1994: Note icebergs and active calving into proglacial lake. Also height of lateral ice margin up valley sides.

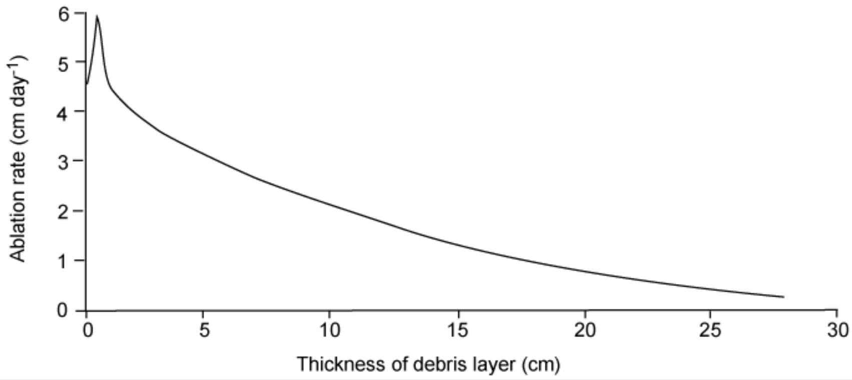
1998: Snout retreated from calving position. Deposition taking place proglacially, particularly around latero-frontal positions; ice height on eastern side of glacier significantly lower.



2004: Snout area in full retreat. Supply of ice over icefall down to minimum amount to sustain active flow. Rock base beneath icefall becoming visible. Marginal debris undergoing collapse/removal.

C

E



A: Basic mechanisms of glacier flow.
B: Air photograph of Gigjökull taken in 1960. Note the surface patterns of crevassing, and also the relative amounts of debris on the surface in the upper and lower portions of the glacier.
C: Illustration of flow within glaciers. Debris is from a USAF Liberator which crashed on the Eyjafjall summit in 1947. Only now is the wreckage appearing at the toe of the glacier.
D: Sequence of photographs illustrating recent retreat of Gigjökull.
E: Relationship between glacier surface debris cover thickness and ablation. Shielding effects of overburden have a significant impact on glacier recession.

UNIT 2: STEINHOLTSJÖKULL

1967 Steinholtshlaup and its geomorphological legacy

UNIT 2: STEINHOLTSJÖKULL *1967 Steinholtshlaup and its geomorphological legacy*

Steinholtsjökull is, like Gigjökull, a small, steep, northward flowing outlet glacier of the Eyjafjallajökull ice cap. Unlike Gigjökull, the glacier is sourced on the eastern flank of the volcanic massif, not directly from the crater. In its lower reaches the glacier flows in a deep trough which curves around to the west. The glacier was once considerably more extensive, depositing moraines on the plateau to the north of the glacier terminus (Kirkbride & Dugmore, in press). In 1967 a large section of the valley side collapsed onto the glacier margin. The slide plane continued 30m below the base of the glacier, causing the displacement of a large portion of the glacier margin. This ice, in combination with much of the rock-fall debris created a catastrophic 'hlaup' event, displacing and mixing with water in a large proglacial lake under intense air pressure (Kjartansson, 1967). This hlaup flowed downvalley as a high-energy outburst flood, transporting large boulders ($80m^3$ or >50 tonnes) and ice blocks for several kilometres (Kjartansson, 1967). At its peak it is estimated that discharge reached $2100m^3$/sec.

The glacier foreland exhibits clear geomorphological evidence of the flood. Immediately following the event a veneer of debris covered slopes in the Steinholtsa valley up to 75m above the valley floor. Large boulders and erosional channels attest to the power of the flood, whilst hummocks and dead-ice hollows relate to deposition in the quiescent phase. The collective landsystem is evidence of a modern low-frequency, high-magnitude event within a glacial system. The ice-front advanced during the 1970s and oscillated around the same position in the 1980s. Noticeable thinning and surface modification of the glacier has occurred since 1995.

The **aims** of this unit are:

1. to introduce the concept of glaciers as a dynamic geological system.

2. to demonstrate the delicate interplay between the landscape and glacier dynamics.

3. to examine evidence of a recent low-frequency, high-magnitude event in the geological record.

Research questions:

1. What are the prominent indicators of *hlaup* activity that can be found in the depositional record, both contemporary and ancient?

2. How important are these events in our understanding of the glacial environment?

3. To what extent are deposits similar to those found in the Steinholtsa valley to be expected in British Quaternary environments?

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Kjartansson, G. 1967. The Steinholtshlaup, central south Iceland, on January 15th 1967. *Jökull* **17**: 249-262.

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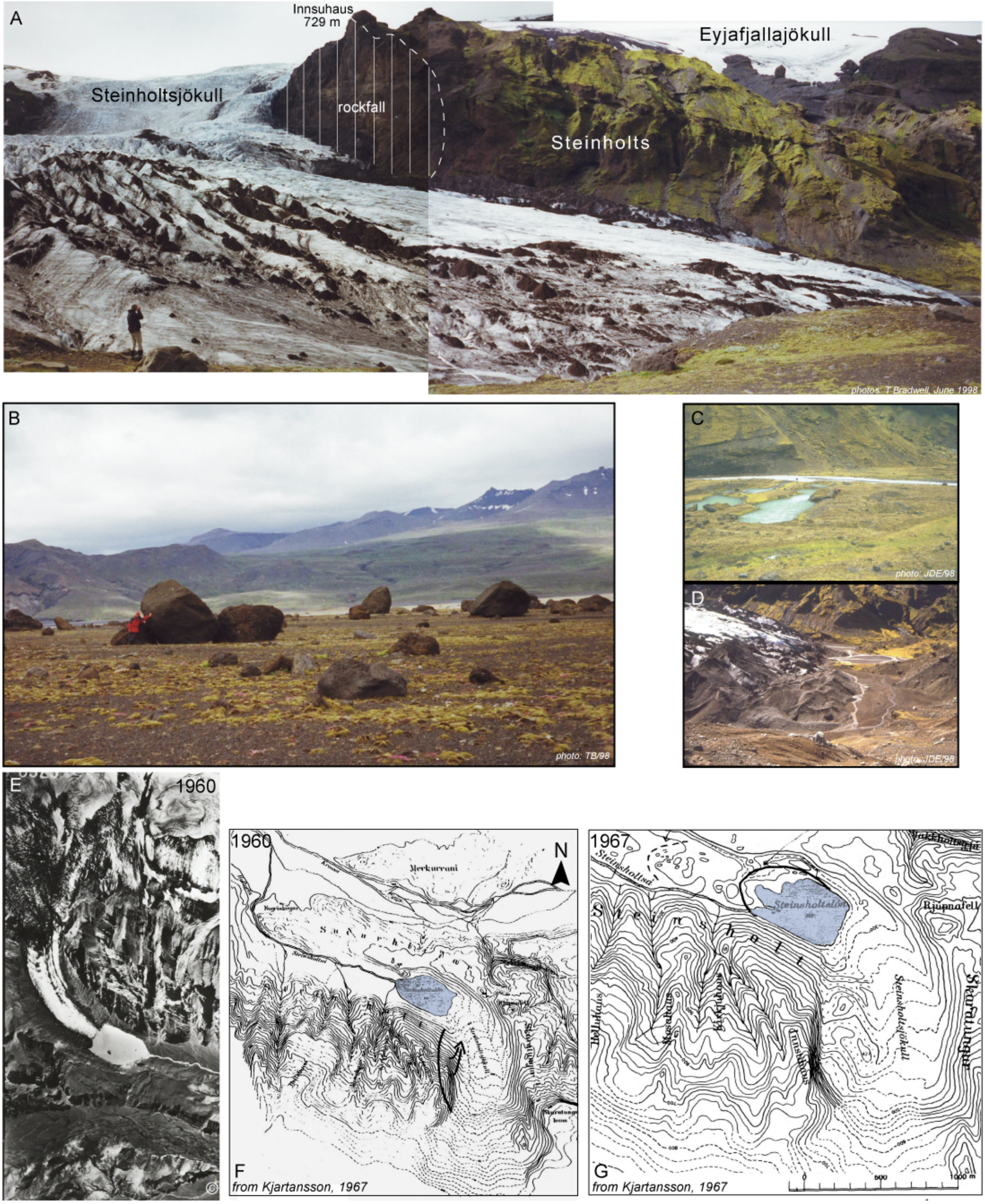
UNIT 2: STEINHOLTSJÖKULL *1967 Steinholtshlaup and its geomorphological legacy*



A: Panoramic view of Steinholtsjökull. The failure face of the 1967 rockfall can be clearly seen beneath Innsuhaus, to the west of the icefall.

B: Boulders deposited by the hlaup in the Steinholtsa Valley. Some of these are 80m^3 (Kjartansson, 1967) and over 4m in diameter. Transport was facilitated by a combination of compressed air, as a result of the fall, and the integration of lakewater from the Steinholtslon.

C: Kettle holes resulting from ice-block meltout of larger fragments of the glacier, broken off during the rockfall.

D: The modern terminus of Steinholtsjökull (1998). The Steinholtslon was overridden in the 1970s by the advance of the glacier snout. Larger debris cones in this area tend to be ice cored - a further legacy of the hlaup.

E: Air photo of Steinholtsjökull in 1960, prior to the hlaup.

F: The Steinholtsa valley prior to the rockslide in 1960. Note the regular profile of the valley floor west of Steinholtslon.

G: The Steinholtsa valley after the rockslide in 1967. Note the more chaotic proglacial area, resulting from disruption of the snout during the hlaup, and the effect on the glacier surface itself, immediately below the failure face. Debris deposited onto the ice formed a 'vast heap', though actual volumes were difficult to determine at the time. The slide plane continued beneath the glacier at a depth of some 30m, resulting in the removal of a significant portion of the western part of the glacier, and the commensurate large volume of hlaup material being transported down the Steinholtsa and Markarflot Valleys.

UNIT 3: MARKARFLJOT

Glaciofluvial sheet deposits (sandar)

UNIT 3: MARKARFLJOT *Glaciofluvial sheet deposits (sandar)*

The **Markarfljot** is a large coastal plain of coalescent braided-river sediments deposited by meltwater issuing from several glaciers in the Thorsmork district. This sheet of glaciofluvial sediments or *sandur* has been forming since deglaciation started at the end of the Late Devensian, and has been actively prograding throughout much of the last 10,000 years (Krigstrom, 1962). The Markarfljot glaciofluvial-valley fill attains a thickness of >250 m and extends 30 km downstream from glacier termini (Haraldsson, 1981).

Sediments in the Markarfljot sandur range in size from large boulders to fine sand and silt – the majority being gravel and cobble grade. The aggradation and migration of bedforms and larger-scale dunes, bars and channels produce a wide range of lithofacies associations. Sandur deposits on the Markarfljot accrete in complex lateral (transverse) bars (Maizels, 1991). Directional structures within the bars are more variable in orientation than the channels which contain them. Different directional structures record different stages of the flow: imbrication and lineation form mainly in response to high flow stage; whilst cross-stratification records the lower stages of flow (Miall, 1978).

It has been suggested that low-frequency, high-magnitude flood events or *jökulhlaup* may play a key role in long-term sandur development in southern Iceland (Maizels, 1991). However, Markarfljot has experienced very few catastrophic outburst floods in historical times (since ~AD 900) (Smith, 2004).

The **aims** of this unit are:

1. to recognise glaciofluvial outwash deposits (sandar), their regional extent and development history.

2. to recognise the sediment lithofacies associated with glaciofluvial sheet deposits.

3. to understand the concept of glacial sediment recycling from the ice-margin to the sediment sink.

Research questions:

1. How can the lithofacies found in sandur be used to determine a history of formation?

2. What are the key sedimentological indicators of flow regimes in sandur deposits?

3. To what extent are these characteristic lithofacies able to provide information about the wider palaeoenvironmental changes occurring within the Markarfljot catchment?

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Haraldsson, H. 1981. The Markarfljot sandur area, south Iceland: sedimentological, petrographical and stratigraphic studies. *Striae*, **15**: 15-56.

Krigstrom, A. 1962. Geomorphological studies of sandur plains and their braided rivers in Iceland. *Geografiska Annaler*, **44**: 328-346.

Maizels, J.K. 1991. The origin and evolution of Holocene sandur deposits in areas of Jökulhlaup drainage, Iceland. *In*: Maizels, J.K. & Caseldine, C.J. (Eds) *Environmental Change in Iceland: Past and Present*: 267-302. Kluwer, Dordrecht.

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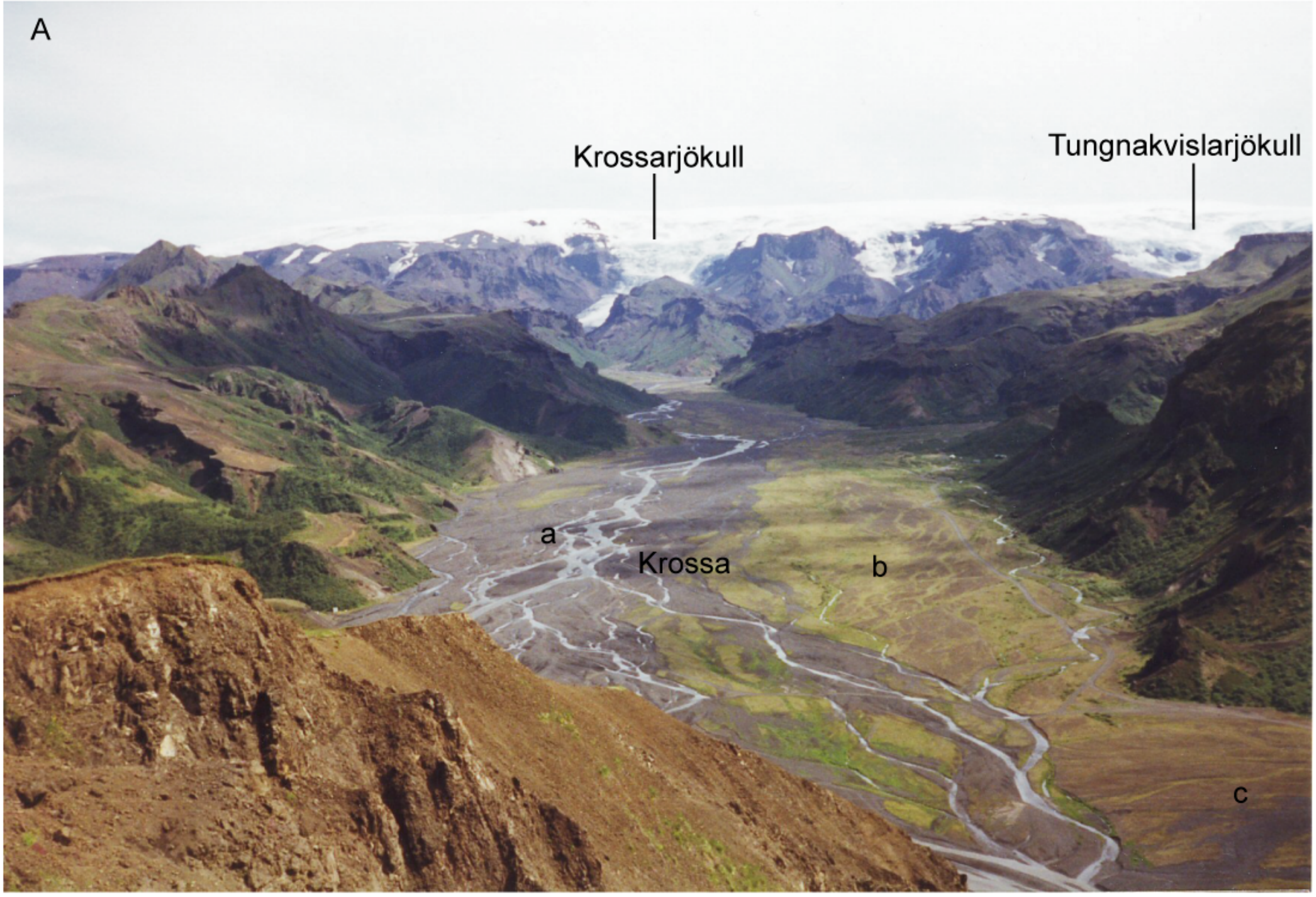
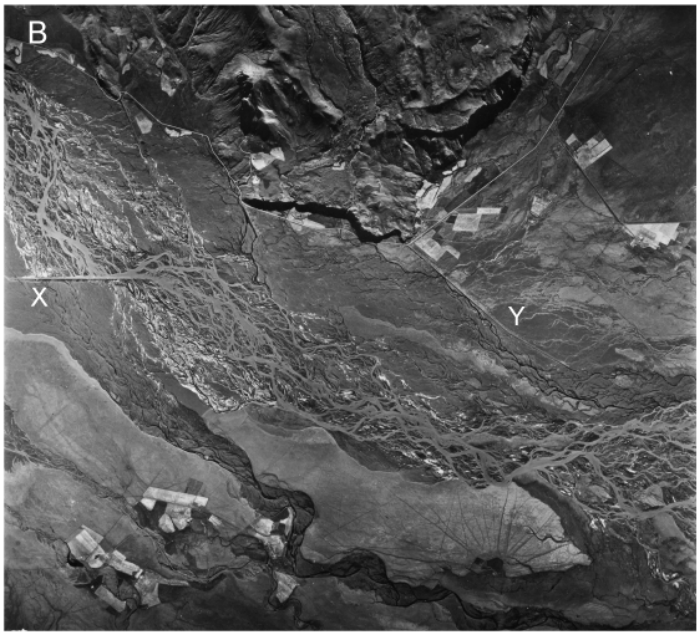
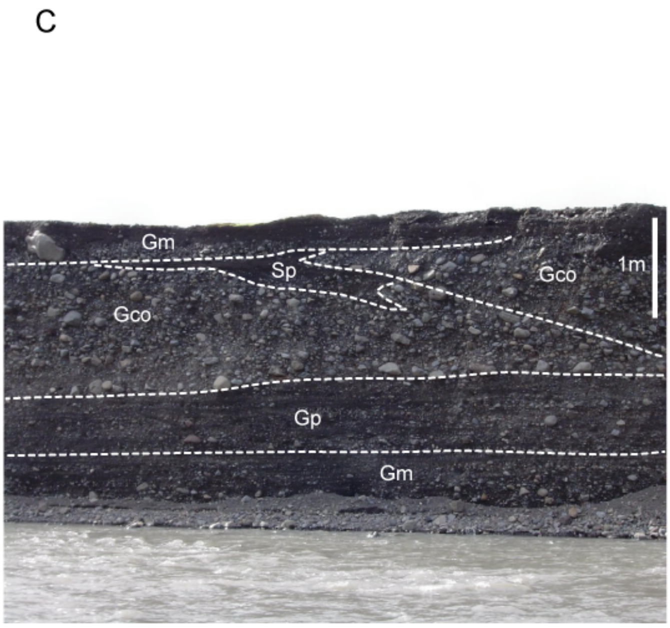
UNIT 3: MARKARFLJOT *Glaciofluvial sheet deposits (sandar)*



A. The Krossa River, the major upstream tributary of the Markarfljot, is fed by the glaciers of SE Myrdalsjökull: Krossarjökull and Tungnakvislar-jökull.

a. Active river channels, forming part of the overall braided channel system (sandur).
b. Abandoned palaeo-channels, now partially infilled by infrequent flood deposits, plus wind blown sand and fines.
c. Low-relief, largely inactive, outwash fan extending into the Krossa Valley from Merkurtungnul.





B. Aerial photograph of the lower Markarfljot River, taken in 1960, showing the extensive braided channel system (sandur). This far downstream, discharge has been significantly increased by meltwater from Gigjökull and Steinholtsjökull, plus snowmelt runoff from the Eyjafjallajökull and Tindfjallajökull ice caps. Note the floodwater defences (X, Y) along the edges of the channel installed to protect farms on the vegetated sandur.

C. Section in the banks of the Markarfljot, near Thorsmork, showing typical lithofacies of a braided channel system. Note the cross bedding indicating flow from left to right, overlying horizontally bedded facies, illustrating the velocity changes in glacial river systems.

UNIT 4: LANGANES
Paraglacial fans and sediment sequences

UNIT 4: LANGANES *Paraglacial fans and sediment sequences*

Langanes lies on the southern flanks of the Markarfljot Valley, and is characterised by a series of coalescent alluvial and glaciofluvial fans. These fans are up to 1.5km wide at the toe, and 1.5km long from toe to apex. They were deposited chiefly by meltwater issuing from the Eyjafjallajökull ice cap. The ice cap has been retreating and thinning since attaining its recent maximum during the Little Ice Age (~AD 1600-1900).

The construction, progradation and dissection of the fans throughout the Holocene reflects the nature of ice-cap retreat on Eyjafjallajökull. During the Little Ice Age the eastern fans received sediments directly from ice-marginal streams (Dugmore, 1987). Over the course of the last two centuries these fans have become largely inactive, experiencing periodic incision during high-magnitude rainstorms. The older fans are truly paraglacial; being conditioned by glaciers in their catchment, but not being a direct product of glaciation.

The examination of lithofacies within the fan sediments can allow palaeogeographical reconstruction to be made. In combination with dating techniques, such as lichenometry and tephrastratigraphy, the recognition of sediment packages within the fans may enable the rates of fan formation, the timing of incision, and age of fan surfaces to be ascertained.

The **aims** of this unit are:

1. to recognise the morphology and processes operating on glaciofluvial and alluvial fans.

2. to recognise the sediment lithofacies associated with glaciofluvial and alluvial fans.

3. to understand the concept of the paraglacial landsystem.

Research questions:

1. What are the key lithofacies types associated with fan deposits?

2. To what extent are the characteristic lithofacies, in combination with dating techniques, able to provide information regarding the temporal and spatial variability of fan formation. How can this be related to the dynamics of the Eyjafjallajökull ice cap?

3. How applicable is the concept of *paraglaciation* in modern and ancient landscapes.

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Rachocki, A.H. & Church, M. (eds) 1990. *Alluvial Fans: A Field Approach*. Wiley, Chichester.

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Dugmore, A.J. 1987. *Holocene glacier fluctuations around Eyjafjallajökull, south Iceland: a tephrochronological study*. Unpub. PhD thesis, University of Aberdeen.

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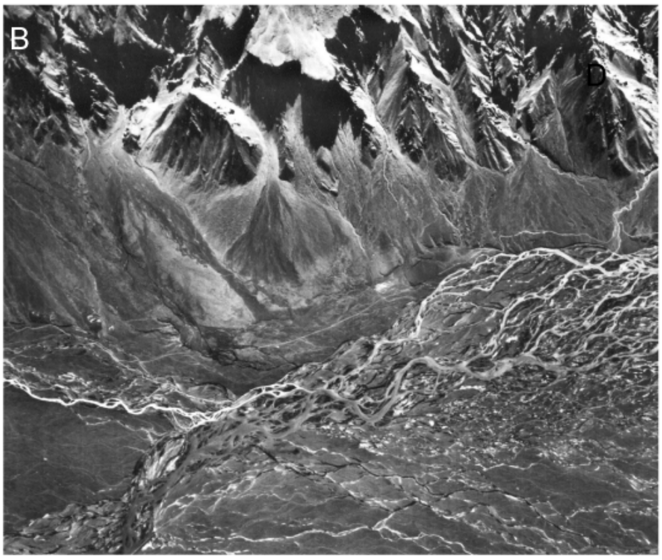
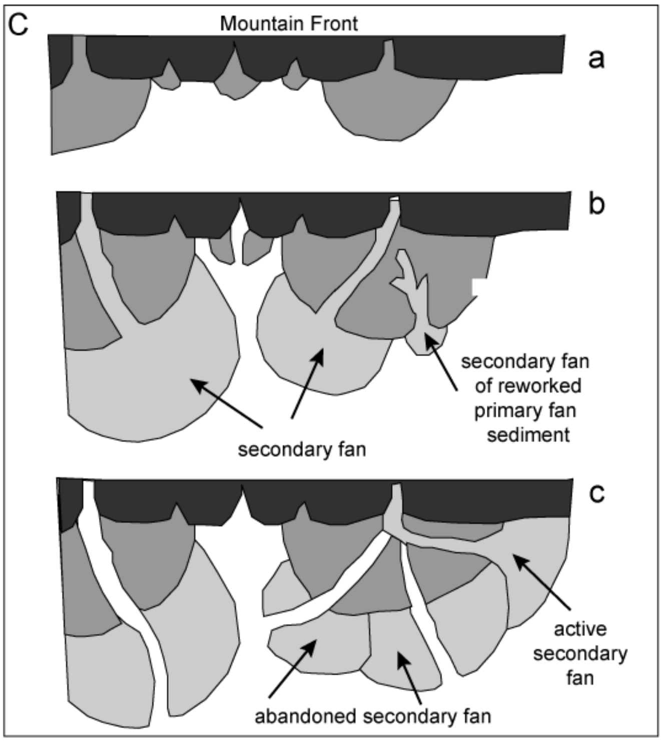
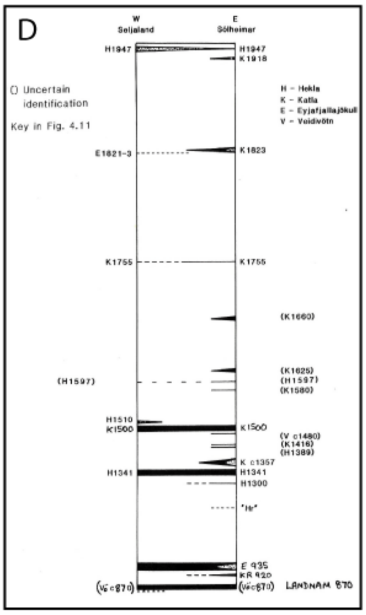
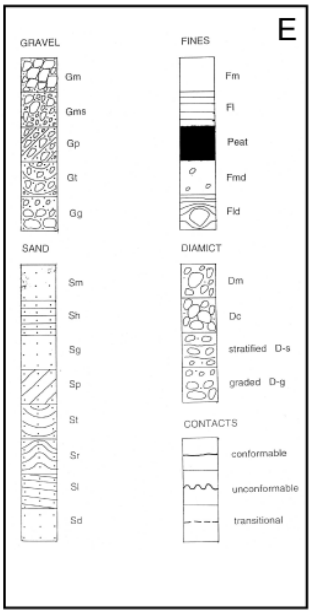
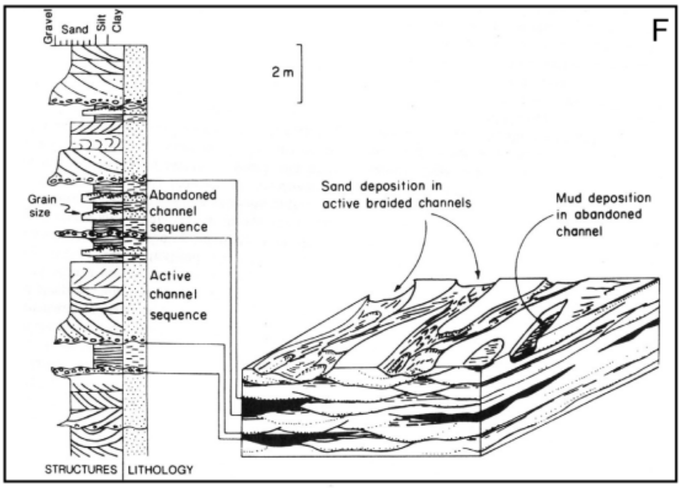
UNIT 4: LANGANES *Paraglacial fans and sediment sequences*

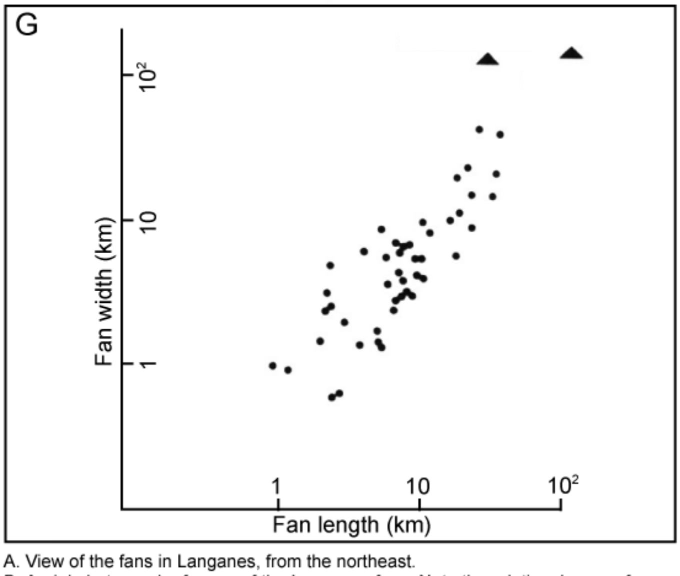












A. View of the fans in Langanes, from the northeast.
B. Aerial photograph of some of the Langanes fans. Note the relative degree of stability between fan surfaces (shown as grey shades), reflecting changing meltwater sources from the retreating icecap on the plateau above.
C. Schematic figure of secondary fan development subsequent to fanhead entrenchment and primary fan reworking *(from Denny, 1967).*
D. Summary of historical tephra stratigraphy found in the Langanes study area *(from Dugmore, 1987).*
E. Lithofacies symbology used in sedimentary logging *(modified from Miall, 1978).*
F. Typical alluvial fan stratigraphy where sedimentation occurs in a rapidly shifting complex of channels (*from Selley, 1976*).
G. The dimensions of recent alluvial and paraglacial fans showing length/width relationships *(from Heward, 1978).*

UNIT 5: SOLHEIMAJÖKULL
Ice-margin fluctuations

UNIT 5: SOLHEIMAJÖKULL *Ice-margin fluctuations*

Solheimajökull is a 15-km long outlet glacier of the Myrdalsjökull ice cap in southern Iceland. The glacier has an altitude range from 1500-100 m asl, and is sourced on the southern portion of the Katla central volcano. The glacier covers 42 km^2 and drains through a broad trough in its lower reaches. Ice-radar surveys have revealed that this trough lies >50 m below sea level in places and that the ice is up to 300m thick in the glacier trunk. Solheimajökull has been monitored sporadically since c. AD 1700 and annually since 1932. The glacier is one of the most easily accessible in Iceland and, consequently, has been the focus of several detailed palaeo-environmental and glaciological studies (eg. Dugmore, 1987; Taylor, 1998; Mackintosh, 2000).

The large-scale fluctuations experienced by Solheimajökull during the Holocene are unprecedented in Iceland. This fact led some to suggest that the glacier was responding to ice-divide migration rather than simply climatic forcing (Dugmore & Sugden, 1991). The topography of the Myrdalsjökull ice cap would be well suited to such a phenomenon. However, recent modelling studies have shown that the glacier fluctuations could be simply in response to climatic change (Mackintosh *et al*., 2002). The length of the glacier being partly responsible for the long response time of the ice margin to perturbations in ELA. It is also possible that the fluctuations of Solheimajökull are related to geothermal changes beneath the ice.

The **aims** of this unit are:

1. to examine the processes operating at a present-day ice margin.
2. to identify the geological record of former ice margins on the glacier foreland.
3. to understand the link between glacier fluctuations and climatic forcing factors.

Research questions:

1. Is the glacier currently in equilibrium with the climatic conditions?
2. What is the preservation potential of the glacial geomorphology relating to a dynamic, climatically sensitive, glacier such as Solheimajökull?
3. Do the anomalous fluctuations of Solheimajökull reflect ice-divide migration?

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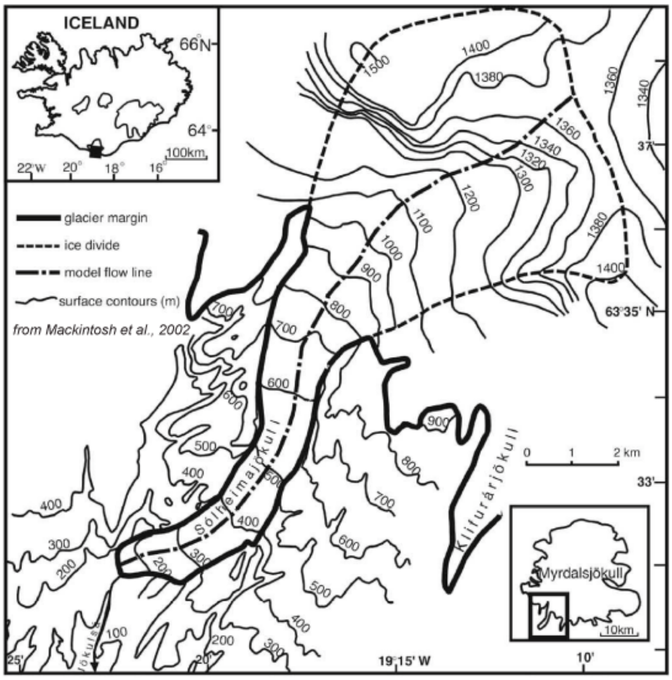
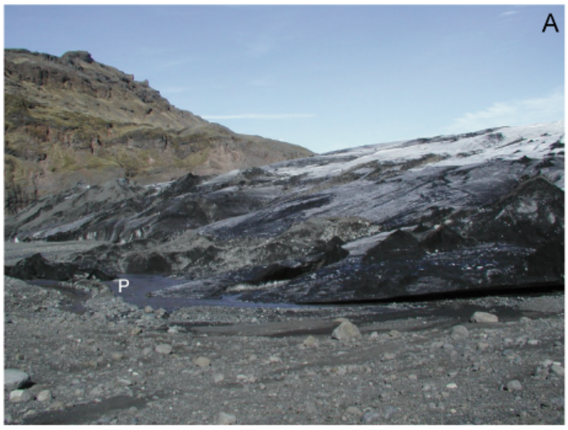
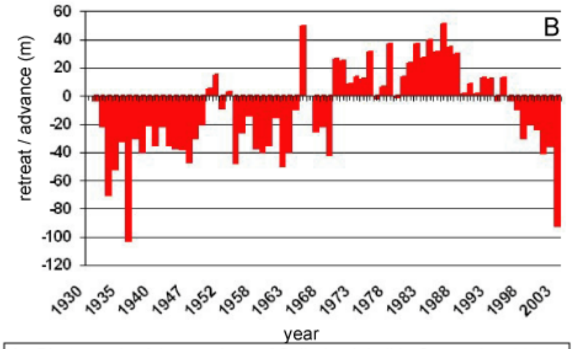
UNIT 5: SOLHEIMAJÖKULL *Ice-margin fluctuations*





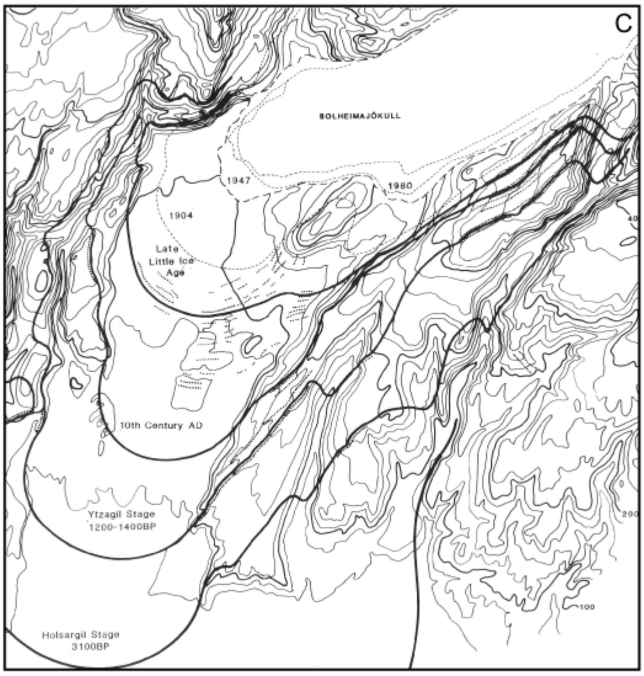


A. Photograph of the terminus of Solheimajökull in September 2004. Note the dirty margin and typical sedimentology of recently exposed subglacial sediments. A small push moraine (P) has formed at the ice edge (<0.5m high). Photograph: O.Ingolfsson (www.hi.is).

B. Measured fluctuations of Solheimajökull's ice margin since 1930 *(from Einarsson, 2005)*.

C. Holocene fluctuations of Solheimajökull, reconstructed from geomorphological, tephrochronological and, since 1904, cartographic and photographic evidence *(from Dugmore, 1987)*.

D. The margin of Solheimajökull following the 1999 jökulhlaup. Note the small water-streamlined 'flute' in the foreground.
E. A small englacial meltwater conduit emerging at the ice margin.
F. Small pits and kettle holes formed by melting ice blocks deposited by flood waters in 1999. Photos: O.Ingolfsson (www.hi.is).



UNIT 6: SKEIDARARJÖKULL

Jökulhlaup

UNIT 6: SKEIDARARJÖKULL *Jökulhlaup*

Skeidarajökull is a large outlet glacier draining the southern margin of Vatnajokull – the largest ice mass in Europe. Skeidarajökull has a total area of 160 km^2 with an ice front 25km wide. It is the largest of the Icelandic glaciers and has surged several times in the last ~300 years. It is also commonly affected by glacier outburst floods or *jökulhlaup*. The largest in Iceland's history, and most recent, being on November 6-7th 1996 (Jonsson *et al*., 1998).

Various aspects of the geomorphological and sedimentological legacy of the 1996 jökulhlaup on Skeidararsandur have been studied in detail by numerous researchers (eg. Russell & Marren, 1999; Roberts *et al*., 2000)

The **aims** of this unit are:

1. to recognise the range of sediments and landforms associated with glacier outburst floods (jökulhlaups).

2. to examine evidence relating to the erosional and depositional regimes within a high-magnitude, low-frequency flood event.

3. to examine the legacy of the 1996 Skeidara jökulhlaup.

Research questions:

1. Can palaeo-outburst floods be recognised in the landscape?

2. How often do jökulhlaups occur, can they be predicted and what are the hazards to humans?

3. How old is the buried ice in the Gigjukvisl section and how long is it likely to survive?

References:

Everest, J.D., Bradwell, T. 2003. Buried glacier ice in southern Iceland and its wider significance. *Geomorphology,* **52***: 347-358.*

Maizels, J.K. 1991. The origin and evolution of Holocene sandur deposits in areas of jökulhlaup drainage, Iceland. In: Maizels, J.K. and Caseldine, C. (eds) *Environmental change in Iceland: Past and present*. Dordrecht: 267-302.

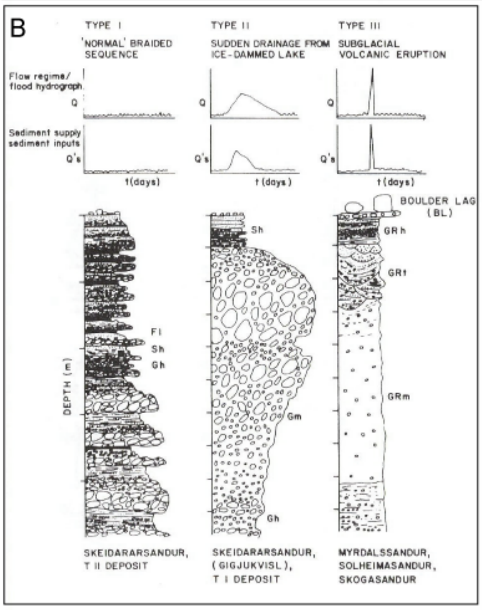
Jonsson, S., Adam, N., Bjornsson, H., 1998. Effects of subglacial geothermal activity observed by satellite radar interferometry. *Geophysical Research Letters*, **25**: 1059-1062,

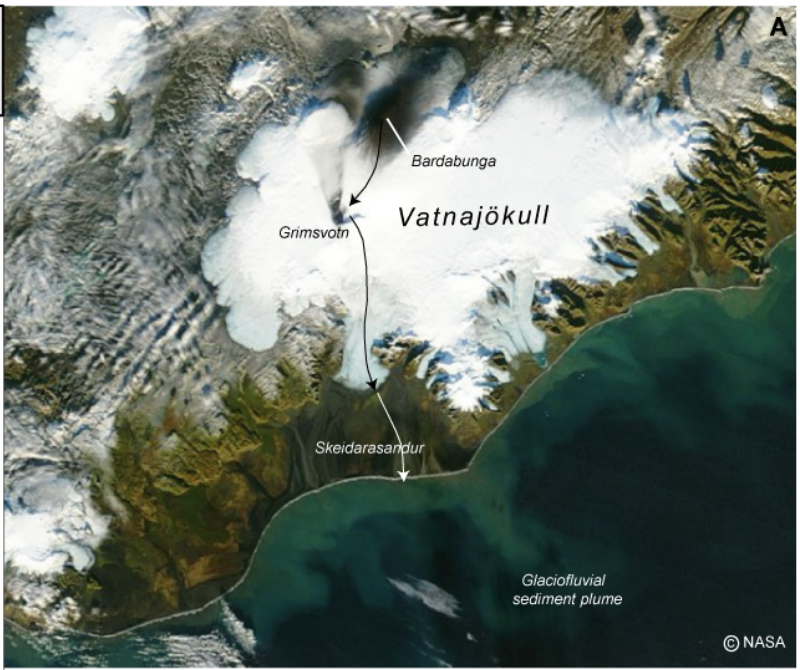
Roberts, M.J., Russell, A.J., Tweed, F.S. & Knudsen, Ó., 2001. Controls on englacial sediment deposition during the November 1996 jökulhlaup, Skeiðarárjökull, Iceland. Earth Surface Processes & Landforms, 26, 935-952.

Russell, A. J. & Marren, P. M. 1999: Proglacial fluvial sedimentary sequences in Greenland and Iceland: a case study from active proglacial environments subject to jökulhlaups. In Jones, A. P., Tucker, M. E. & Hart, J. K. (eds.): *The Description and Analysis of Quaternary Stratigraphy Field Sections*, 171-208. QRA Technical Guide No. 7.

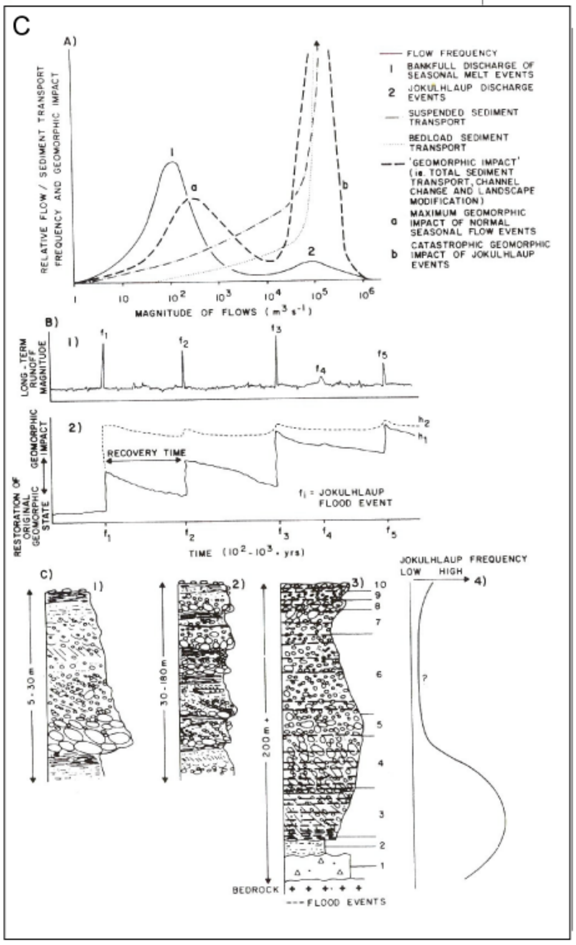
UNIT 6: SKEIDARARJÖKULL *Jökulhlaup*

***Jökulhlaup**: a catastrophic outburst flood, often caused by a subglacial eruption. Peak floods commonly last less than 24 hours and may reach discharges of 100,000 $m^3 s^{-1}$. The largest in history occurred on 7/11/1996.*





A. Satellite image of southeast Iceland taken in 1996 whilst Bardabunga was erupting.The water produced by subglacial melting followed the route shown by arrows, emerging at the ice margin.



Gigjukvisl river (in flood)
November 6, 1996

Gigjukvisl River
(post Jokulhlaup)
December 12, 1997

B. Vertical lithofacies models of glaciofluvial sheet (sandur) development in areas of different characteristic meltwater flow regimes *(from Maizels, 1991)*.
TYPE 1: sandur subject to normal, ablation-controlled seasonal meltwater regime.
TYPE 2: sandur subject to drainage from ice-dammed or subglacial lakes, exhibiting a flood hydrograph extending over a period of days to weeks.
TYPE 3: sandur subject to sudden catastrophic floods generated by subglacial volcanic eruptions, exhibiting highly peaked hydrograph, high sediment concentration and flood duration of a few hours.

C. Simplified models of expected meltwater runoff in areas of jökulhlaup drainage, and associated statigraphic signature*(from Maizels, 1991)*.
D. Large terminal-moraine complex breached by Gigjukvisl flood waters on 6-7th November 1996. Section in Photo E circled.
E. Close up of buried glacier ice overlain by 3m of sand and gravel, within moraine complex; Gigjukvisl. (Photo: T.Bradwell, May 1999. J.Everest for scale.)
F&G. Aerial photographs taken during, and 13 months after the Skeidara jökulhlaup. Photos: O.Ingolfsson (www.oi.is)

UNIT 7: SVINAFELLSJÖKULL

Dating techniques

(i) Lichenometry

Svinafellsjökull is a medium-sized outlet glacier of the Öraefajökull ice cap. The trunk of the glacier is 8 km long and flows from a high-level accumulation area on the northern part of the ice cap. The glacier descends via a series of ice-falls in its upper reaches but has a low gradient for much of its length. Svinafellsjökull is flanked by mountains, Hafrafell (1180m), Hrutsfjall (1875m) and Hvannadalshnukur (2119 m), that provide a stunning backdrop. During the 18th and 19th centuries the glacier was more extensive and coalesced with Skaftafellsjökull to form a broad piedmont lobe. The glaciers separated c.1930. Moraines on the proglacial foreland at Svinafellsjökull detail the history of ice-marginal fluctuations during the late Holocene. The geomorphic record is unusually well preserved, partly due to the confined meltwater system. Moraines, flutes, kettle holes, proglacial lakes and glaciofluvial deposits are all in evidence. Thompson (1988) mapped the moraines and devised a glacial chronology using lichenometry. The glacier is a favourite for student mapping projects due to its accessibility and clarity of landforms.

The **aims** of this unit are:

1. to recognise the range of landforms found at an actively oscillating glacier front.
2. to understand the concept of 'preservation potential' within the geomorphic record.
3. to understand the concept of lichenometric dating.

Research questions:

1. How can the unusually well-preserved geomorphic record at Svinafellsjökull be explained?
2. What are the advantages and limitations of lichenometric dating?
3. How does the climate affect the glaciology of the glaciers in southern Iceland?

References:

Bradwell, T. 2001a. A new lichenometric dating curve for southeast Iceland. *Geografiska Annaler,* **83A**: 91-101.

Bradwell, T. 2001b. *Glacier fluctuations, lichenometry and climatic change in Iceland*. Unpublished Ph.D. thesis, University of Edinburgh.

Dabski, M. 2002. Dating of the Fláajökull moraine ridges SE Iceland, *Jökull*, **51**: 17-24.

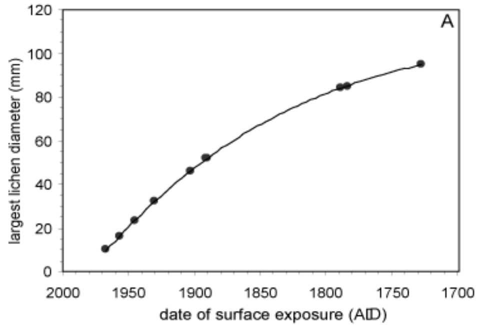
Evans, D.J.A., Archer, S. and Wilson, D.J.H. 1999.. A comparison of the lichenometric and Schmidt hammer dating techniques based on data from the proglacial areas of some Icelandic glaciers. *Quaternary Science Reviews*, **18**: 13-41.

Gordon, J.E. and Sharp, M. 1983. Lichenometry in dating recent glacial landforms and deposits, southeast Iceland. *Boreas,* **12**: 191-200.

Thompson, A. 1988. Historical development of the proglacial landforms of Svinafellsjökull and Skaftafellsjökull, southeast Iceland. *Jökull*, **38**: 17-31.

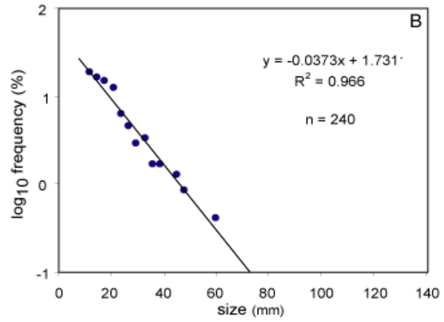
Thompson, A. and Jones, A. 1986. Rates and causes of proglacial river terrace formation in southwest Iceland: An application of lichenometric dating techniques. *Boreas*, **15**: 231-246.

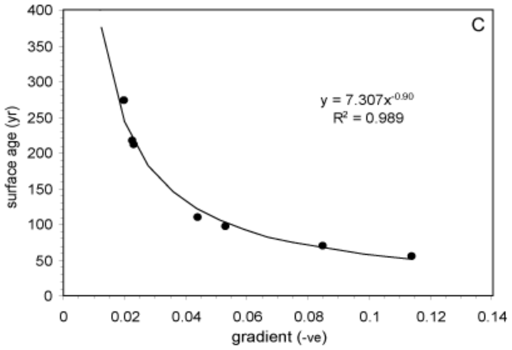
Lichenometric dating: the use of lichen size to determine the age of a surface. The technique is particularly useful when dating surfaces formed within the last 500 years and has a precision of ~10 years when carefully performed.



A. Largest lichen (in a fixed area) vs. surface age in south-east Iceland (section *Rhizocarpon*), *from Bradwell, 2001a.*

B. Typical size-frequency distribution of lichens on moraine.



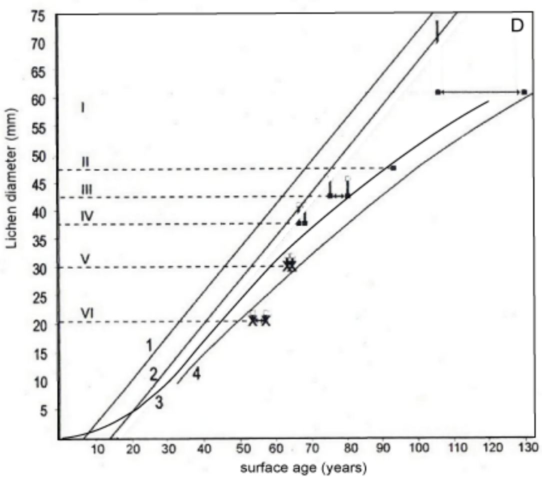


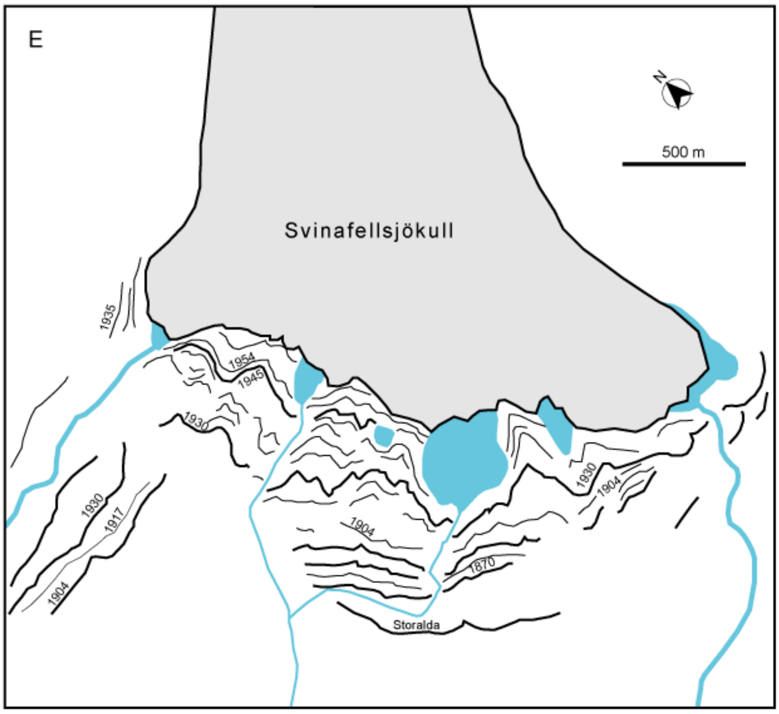
C. Gradient of size-frequency distribution vs. surface age in southeast Iceland *(from Bradwell, 2004).*

D. Largest lichen size vs. surface age in southeast Iceland, according to several studies:

1. Evans et al. (1999)
2. Gordon & Sharp (1983)
3. Thompson & Jones (1986)
4. Bradwell (2001a)

These curves were applied by Dabski (2002) to landforms of known age. The curvilinear forms (3,4) proved most accurate.

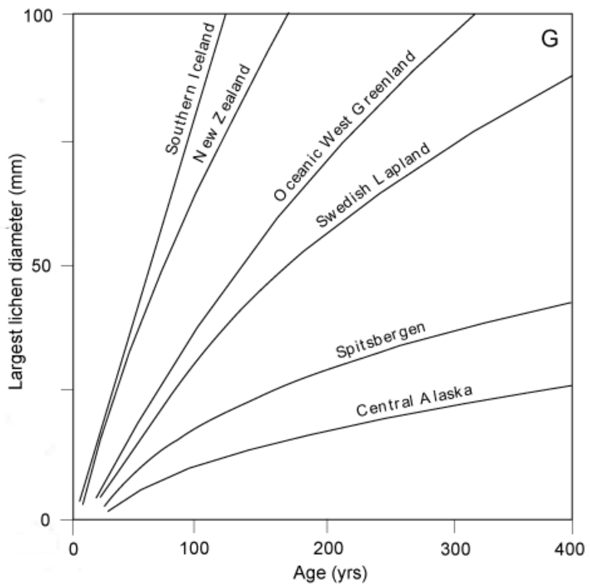




E. Moraines at Svinafellsjökull with lichenometric ages *(from Thompson, 1988).*

F. The largest lichen growing on a glacially deposited boulder can yield a close approximation of the age of deposition. The most commonly used lichen in dating studies is the yellow-green *Rhizocarpon geographicum* species; often distinguished by its black outer rim (P). The thallus shown above (40 mm) is probably c. 60 years old.

G. Lichens are known to grow at different rates in different climates. Growth rates are thought to be related to rainfall frequency and annual temperature range. Note that southern Iceland has some of the fastest lichen growth rates in the world *(from Bradwell, 2001b).*



UNIT 8: SVINAFELLSJÖKULL
Dating techniques
(ii) Tephrochronology

Svinafellsjökull is an 8-km long outlet glacier of the Öraefajökull ice cap. The margin of Svinafellsjökull has fluctuated considerably over the last 10,000 years. During the height of the Weichselian Glaciation southeast Iceland was covered by a large ice sheet that reached to the shelf break, 50 km offshore (Ingolfsson & Norddahl., 1994). Moraines on Skaftafellsheidi testify to a period when the glacier was ~300 m thicker and probably several kilometres longer than at present. *Tephra* from volcanic eruptions has been used to date these early Holocene moraines (Gudmundsson, 1998). During the 9th and 10th centuries, when Iceland was settled by the Norse, glaciers in Iceland were smaller than today. In the 12th and 13th centuries the climate deteriorated and glaciers in the south advanced. The moraine at Storalda is believed to date from this period (Thorarinsson, 1956). The Little Ice Age (~AD 1500-1900) brought severe winters and sea ice to the south coast of Iceland. Glaciers remained in advanced positions for much of the 18th and 19th centuries. The LIA maximum, represented by a large moraine at Svinafellsjökull, is thought to have been deposited c.1870 (Thompson & Jones, 1986; Thompson, 1988)

The **aims** of this unit are:

1. to recognise the range of landforms found at an actively oscillating glacier front.
2. to understand the concept of 'preservation potential' within the geomorphic record.
3. to understand the concept of tephrochronological dating.

Research questions:

1. What are the benefits of the multi-proxy approach to palaeo-environmental studies?
2. What are the advantages and limitations of tephrastratigraphy?
3. What is the age of the Storalda moraine?

References:

Gudmundsson, H.J. 1998. *Holocene Glacier Fluctuations and Tephrochronology of the Öraefi district, Iceland.* Unpublished Ph.D. Thesis, University of Edinburgh.

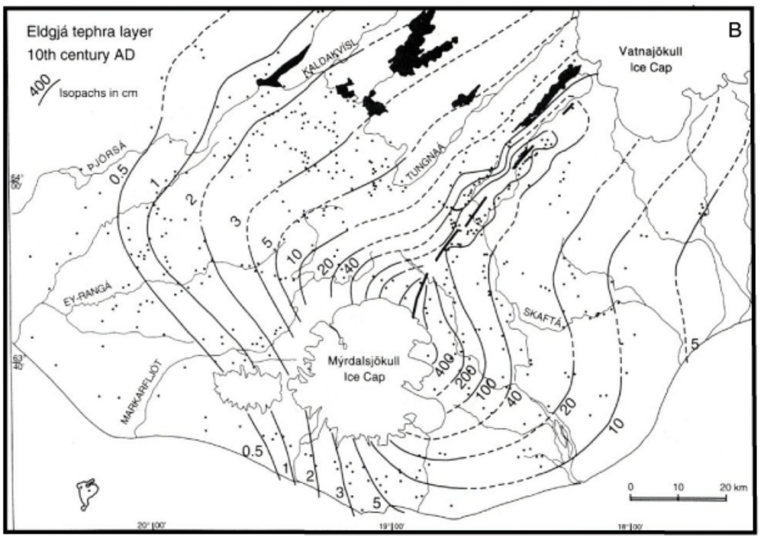
Ingolfsson, O. & Norddahl, H. 1994. A review of the environmental history of Iceland, 13,000-9000 yr BP. *Journal of Quaternary Science,* **9:** 147-150.

Thompson, A. 1988. Historical development of the proglacial landforms of Svinafellsjökull and Skaftafellsjökull, southeast Iceland. *Jökull,* **38:** 17-31.

Thompson, A. and Jones, A. 1986. Rates and causes of proglacial river terrace formation in southwest Iceland: An application of lichenometric dating techniques. *Boreas,* **15:** 231-246.

Thorarinsson, S. 1956: On the variations of Svinafellsjökull, Skaftafellsjökull and Kviarjökull in Öraefi. *Jökull*, **6**, 1-15.

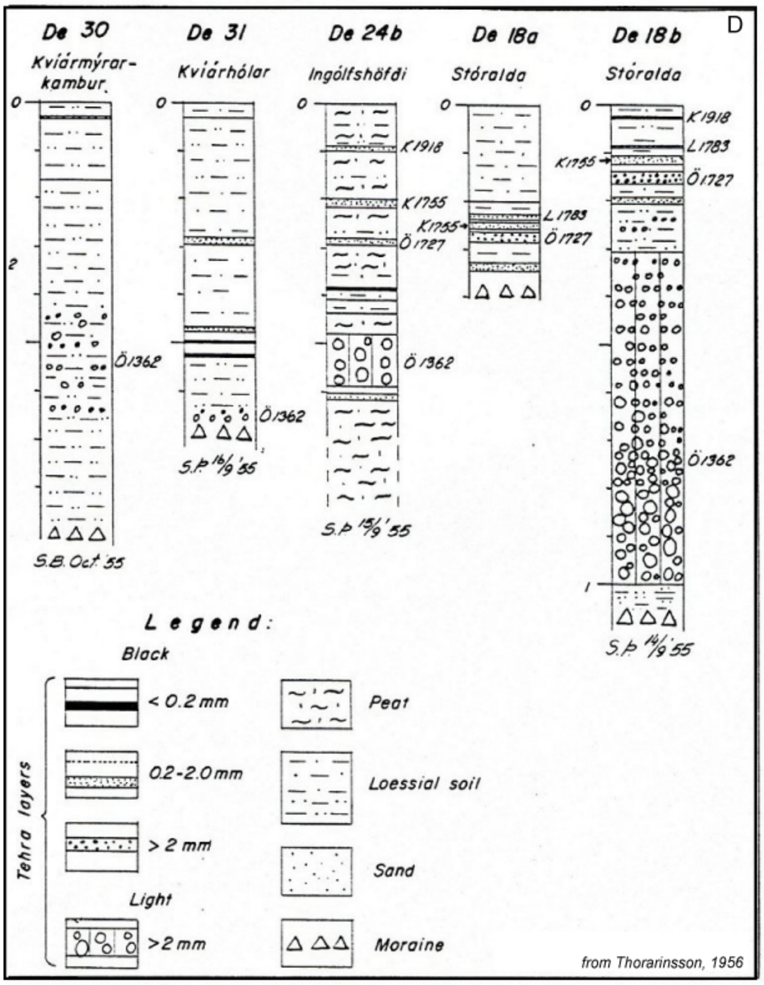
Tephrochronology: the use of volcanic ash layers (tephra) as chronostratigraphic markers to detemine the age of surfaces and landforms. This technique is particularly useful in Iceland where volcanic eruptions occur frequently (every 3-5 years) and are well documented. Icelandic annals record the precise calendar age of ~100 tephras deposited since 900 AD.

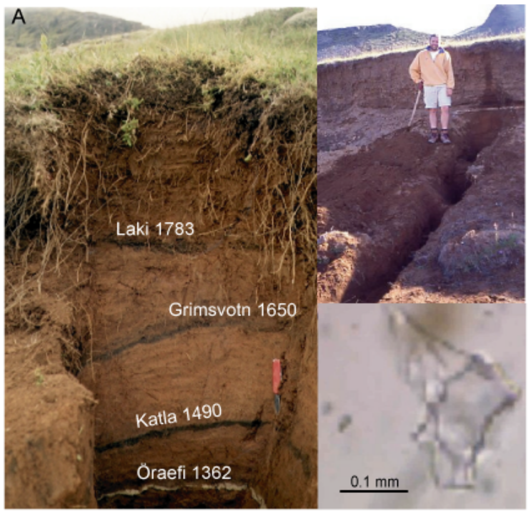


A. Tephra layers in a soil profile near Höfn, used to determine the minimum date of deglaciation. The white layer is from the eruption of Öraefajökull in 1362. Shards of this silicic ash are found across much of southeast Iceland.

B. Isopach map of the Eldgja tephra layer deposited c. 1000 AD *(from Larsen, 1996)*. The source of this ash is clearly visible from the dispersal pattern. Note the thicker blanket E of Myrdalsjökull due to the prevailing wind direction at the time of eruption.

C. Storalda, Svinafellsjökull. Tephra layers in the soil either side of this moraine show that it formed between the eruptions of Öraefi in AD 1362 and 1727 (see D).

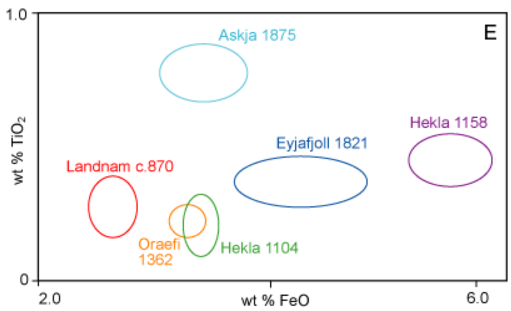


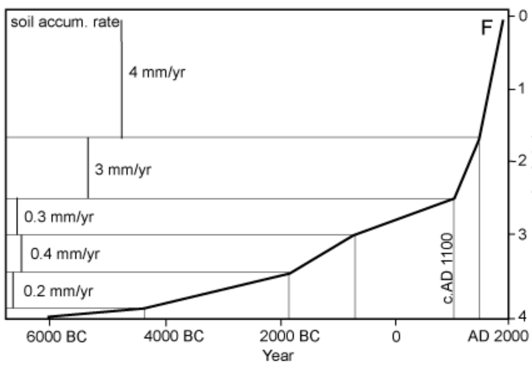


D. Soil profiles from Svinafellsjökull and Kviarjökull *(from Thorarinsson, 1956)*. Pioneering studies by Sigurdur Thorarinsson 50 years ago constrained the age of several large neoglacial moraines in SE Iceland.

E. Volcanic ash can be geochemically 'fingerprinted' to determine its exact origin, when the source is unknown *(from Dugmore et al., 1995)*.

F. Rate of soil accumulation over the last 6000 years in Vatnagardur, southern Iceland, determined by tephrochronology *(from Thorarinsson, 1981)*. Note the rapid increase c.AD 1100, shortly after the time of Norse settlement.





UNIT 9: SKAFTAFELLSJÖKULL
Proglacial foreland evolution

UNIT 9: SKAFTAFELLSJÖKULL *Proglacial foreland evolution*

Skaftafellsjökull is a medium-sized outlet glacier of the Vatnajökull ice cap. The glacier is sourced on the saddle between Vatnajökull and Öraefajökull, with ~20% of the ice coming from Öraefajökull. The main body of the glacier is 10 km long and 2-3 km wide. The glacier carries a relatively low supraglacial debris load. During the Little Ice Age the glacier margin extended 2 km further onto the sandur than at present, and was coalescent with Svinafellsjökull. Thompson & Jones (1986) mapped the foreland of Skaftafellsjökull and dated the moraines using lichenometry. Since the end of the 19^{th} Century, Skaftafellsjökull has undergone punctuated retreat, with noticeable readvances or stillstands centred around 1917, 1930, 1953 and 1982 (Thompson, 1988). The proglacial drainage system has changed considerably over the last ~100 years. The evolution of the sandur has been intimately associated with the development of proglacial lakes and push moraines. Marren (2002) found that glacier retreat at Skaftafellsjökull is accompanied by short-lived rapid incision events of the main meltwater river, rather than gradual fluvial re-adjustment.

The **aims** of this unit are:

1. to recognise the range of landforms found on a modern glacier foreland.

2. to understand the processes responsible for proglacial drainage evolution over the last 100 years.

3. to discuss the specific factors responsible for channel migration at the margin of Skaftafellsjökull since 1995.

Research questions:

1. How rapidly are modern glaciofluvial landforms evolving?

2. In what way does the geomorphology at Skaftafellsjökull resemble a subglacial-proglacial landsystem rather than a glaciated valley landsystem?

3. How might the glaciological response of Skaftafellsjökull's ice margin be influenced by its dual accumulation areas?

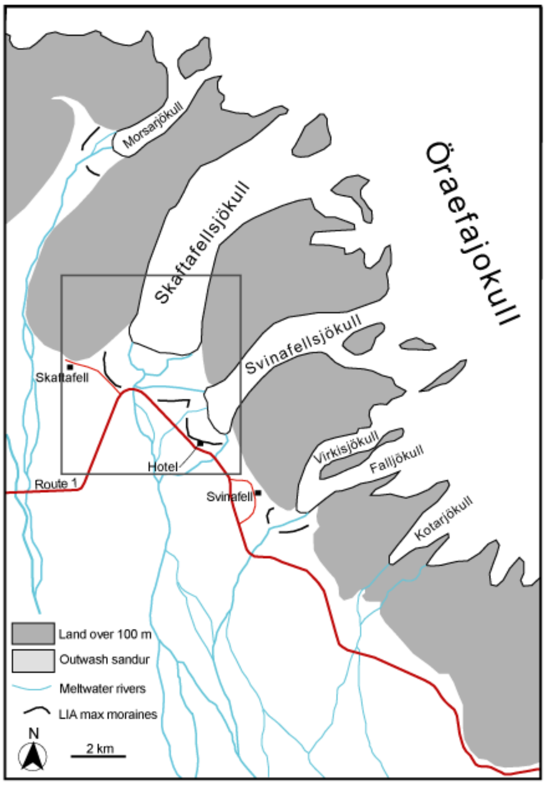
References:

Marren, P. 2002. Glacier margin fluctuations, Skaftafellsjökull, Iceland: implications for sandur evolution. *Boreas*, **31**: 75-81.

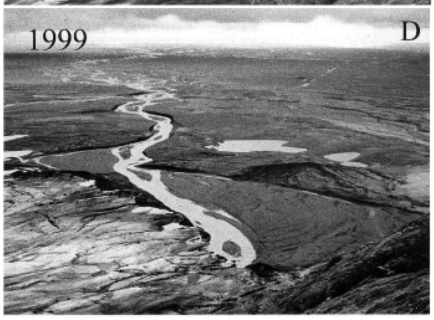
Thompson, A. 1988. Historical development of the proglacial landforms of Svinafellsjökull and Skaftafellsjökull, southeast Iceland. *Jökull*, **38**: 17-31.

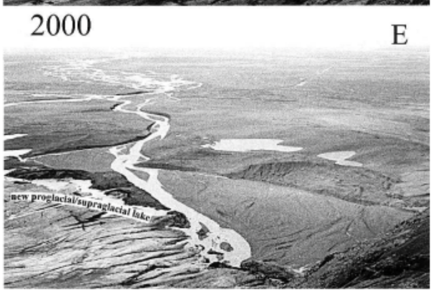
Thompson, A. and Jones, A. 1986. Rates and causes of proglacial river terrace formation in southwest Iceland: An application of lichenometric dating techniques. *Boreas*, **15**: 231-246.

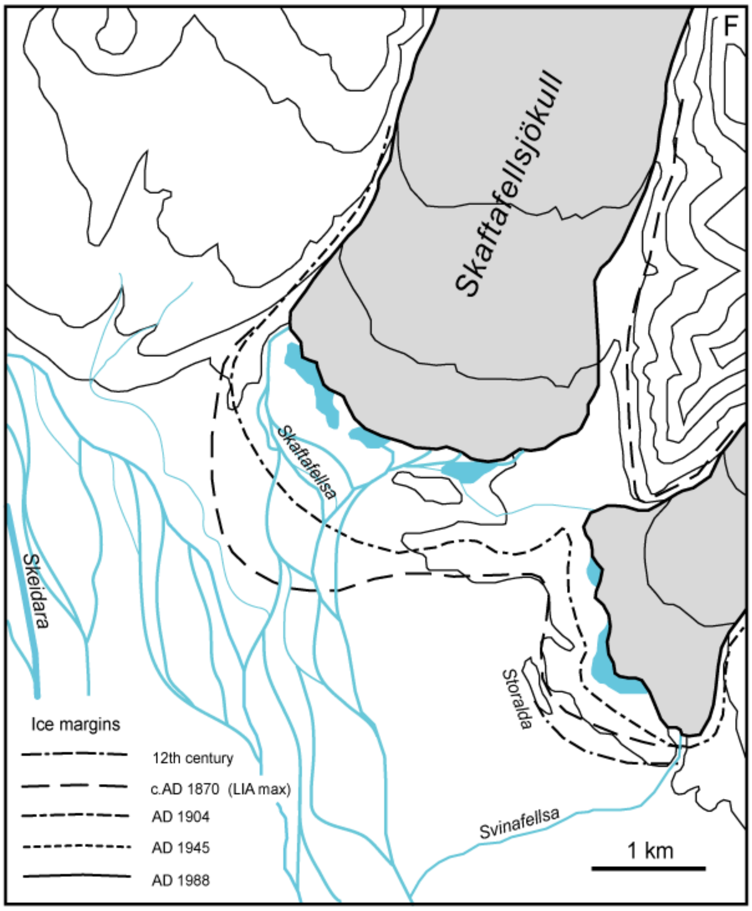
UNIT 9: SKAFTAFELLSJÖKULL *Proglacial foreland evolution*



A. View across the teminus of Skaftafellsjökull from Skaftafellsheidi; Svinafellsjökull in the distance. Note the high number of proglacial lakes on the foreland and the relatively debris-free glacier surface. Photo taken in July 1996.







B-E. Evolution of the proglacial meltwater sytem at Skaftafellsjökull *(from Marren, 1996).*

B. Oblique view of the glacier margin showing the large proglacial channnel system. The prominent moraine is highlighted (photo taken July 1997). Note the meltwater-dissected moraine fragments on the foreland.
C. Photo from same viewpoint in July 1998. Note the anastamosing meltwater channels issuing from numerous points along the glacier margin.
D. Photo from same viewpoint in July 1999. Note the single wide meltwater channel and the abandoned 1999 sandur surface .
E. Photo from the same viewpoint in 2000. Note the single confined channel, as in 1999, and the shallow lake along the glacier margin.
F. The proglacial foreland of Skaftafellsjökull. The map shows the position of the glacier at various times over the late Holocene. The similarity between the ice-marginal positions in c. AD 1300 and c.1870 is striking. The large moraine at Storalda proabably formed a partial barrier to ice-advance during later centuries. The preservation of this moraine is due largely to the confined proglacial meltwater drainage. Pre-LIA moraines are lacking at Skaftafellsjökull *(modified from Thorarinsson, 1956; Thompson, 1988).*

UNIT 10: SKAFTAFELLSHEIDI

Periglacial environments

UNIT 10: SKAFTAFELLSHEIDI *Periglacial environments*

Skaftafellsheidi is the large spur of ice-free upland between Skaftafellsjökull and Morsardalur. The main *heidi* is gently sloping and ranges from 100-550 m in altitude. The mountains of Kristinatindur (1126m) and Skardatindur (1385 m) lie to the NE. During the height of the Weichselian Glaciation, Skaftafellsheidi was covered by a large ice sheet that extended ~50 km offshore (Ingolfsson & Norddahl., 1994). However, some of the highest mountain summits (>1300 m) in southeast Iceland may have been nunataks at this time (Rundgren & Ingolfsson, 1999). Tephrochronological studies have shown that Skaftafellsheidi has probably been ice-free since the mid-Holocene (Gudmundsson, 1998) and, consequently, exhibits a range of periglacial features, such as patterned ground, turf-banked terraces and solifluction lobes. Air temperatures at 500 m OD fluctuate around freezing point over a typical diurnal cycle and snow can persist into the summer months.

The **aims** of this unit are:

1. to recognise the range of sediments and landforms found in a modern periglacial environment.

2. to understand the processes of frost heave, cryoturbation and solifluction.

3. to recognise the main elements of a 'fossil' glacial landscape, broadly comparable in age to those in upland Britain.

Research questions:

1. How fast are modern periglacial processes operating?

2. How effective is the wind as a geomorphic agent?

3. To what extent do geology and sedimentology affect processes of freeze-thaw and solifluction?

4. What gives rise to the unusual patterns on the surface of Morsarjökull glacier? (optional)

References:

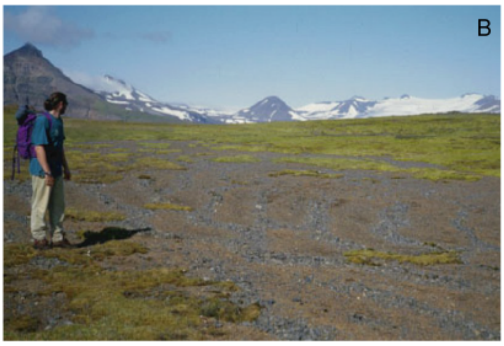
Bradwell, T. 2001. *Glacier fluctuations, lichenometry and climatic change in Iceland*. Unpublished Ph.D. thesis, University of Edinburgh, Scotland.

Gudmundsson, H.J. 1998. *Holocene Glacier Fluctuations and Tephrochronology of the Öræfi district, Iceland*. Unpublished Ph.D. Thesis, University of Edinburgh.

Ingolfsson, Ó. & Norðdahl, H. 1994 A review of the environmental history of Iceland, 13,000-9000 yr BP. *Journal of Quaternary Science*, **9**: 147-150.

Rundgren, M. & Ingolfsson, Ó. 1999. Plant survival in Iceland during periods of glaciation? *Journal of Biogeography*, **26**: 387-396.

UNIT 10: SKAFTAFELLSHEIDI *Periglacial environments*

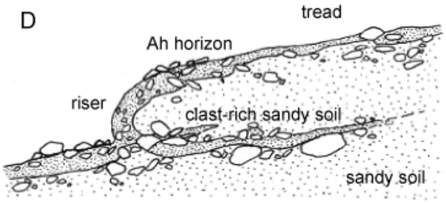


A. Sorted patterned ground is common in SE Iceland above 300m asl where freeze-thaw processes operate year-round. These small scale nets (<0.4m diameter) are actively forming in loose gravel on Skaftafellsheidi.

B. Sorted stripes form on gently sloping ground (<10°), such as these on Dalsheidi at 550m asl. Frost-heaved gravels are sorted by a combination of freeze-thaw action, soil creep and running water. Typical pattern spacing: 1m.

C. Turf-banked lobes and terraces in Fossdalur - striking evidence of solifluction. Note the well-developed bulging fronts suggesting that they are mobile and actively forming. This valley has been free of glaciers for at least 4000 years.

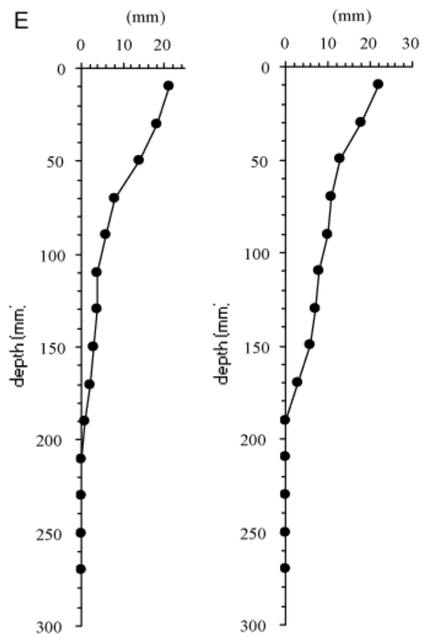
E. Velocity profiles from 2 solifluction terraces on Svinafellsheidi. The points represent Rudberg pillar centres and the horizontal displacement is over 2 years (July 1987-89). Note how downslope displacement decreases with depth, with a maximum of 11mm/yr in the surface layer.



D. Cross-section through turf-banked solifluction lobe showing sedimentology; Fossdalur, SE Iceland *(from Bradwell, 2001)*.

(below) Table summarising morphometric data from 96 solifluction lobes and terraces on Skaftafellsheidi and Svinafellsheidi *(from Douglas & Harrison, 1996)*. All distances in m; angles in degrees. Note the average tread angle is ~0°.

	Riser height	Tread width	Tread length	Riser angle	Tread angle	Lateral angle
mean	0.39	1.58	6.83	34	0	2
min	0.11	0.33	1.40	11	-8	0
max	1.06	6.85	4.08	71	6	7
SD	1.87	1.21	7.38	14	3	2
Q1	0.25	0.91	3.05	23	-3	1
Q2	0.48	1.74	6.94	42	2	3



UNIT 11: VIRKISJÖKULL
Supraglacial debris and ice-stagnation topography

UNIT 11: VIRKISJÖKULL *Supraglacial debris and ice-stagnation topography*

Virkisjökull is a small outlet glacier of the Öraefajökull ice cap. The glacier is actually two ice flows that bifurcate around a central nunatak. The eastern part of the glacier is steep and intensely crevassed and is sometimes referred to as Falljökull ('fall glacier'). The twin glaciers drain from the summit of the Öraefajökull volcano (2119m) and have a collective catchment of ~15 km^2. The glacier served as a routeway for the jökulhlaup of AD 1362, following the eruption of Öraefajökull. Large boulders and the deep rock-cut Falljökulkvisl channel testify to this catastrophic meltwater event.

In the late 1970s, Eyles conducted his now-classic study on supraglacial sedimentation and ice-stagnation topography at Virkisjökull. He was also an early pioneer of the glacial landsystems approach, using landforms at Virkisjökull as an analogue for hummocky moraine formation in Scotland (Boulton & Eyles, 1979; Eyles, 1983). More recently, Bradwell (1998) mapped the complex system of moraines at Virkisjökull and reconstructed the chronology of deglaciation using lichenometry. Everest & Bradwell (2003) used resistivity surveys to verify the presence of buried ice within the chaotic topography on the foreland.

The **aims** of this unit are:

1. to recognise the range of sediments and landforms associated with supraglacial debris supply to the glacier margin.

2. to examine ongoing geomorphic processes at the ice margin and in an area of ice-cored terrain.

3. to critically examine the process of *topographic inversion* and the generation of hummocky moraine (cf. Eyles, 1979).

Research questions:

1. By what processes has supraglacial debris accumulated on Virkisjökull?

2. What are the implications of this case study for hummocky moraines in formerly glaciated terrain (eg. upland Britain), particularly regarding the rate and mode of dead-ice meltout in maritime climates.

3. What is the geological legacy of the 1362 jökulhlaup?

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Boulton, G.S. & Eyles, N. 1979. Sedimentation by valley glaciers: a model and genetic classification. In: C. Schlüchter (Ed). *Moraines and Varves*, Balkema Press, Rotterdam: 11-24.

Bradwell, T. 1998. Climate induced twentieth-century glacier fluctuations in southeast Iceland. *Fróðskaparrit*, **46**: 319-332.

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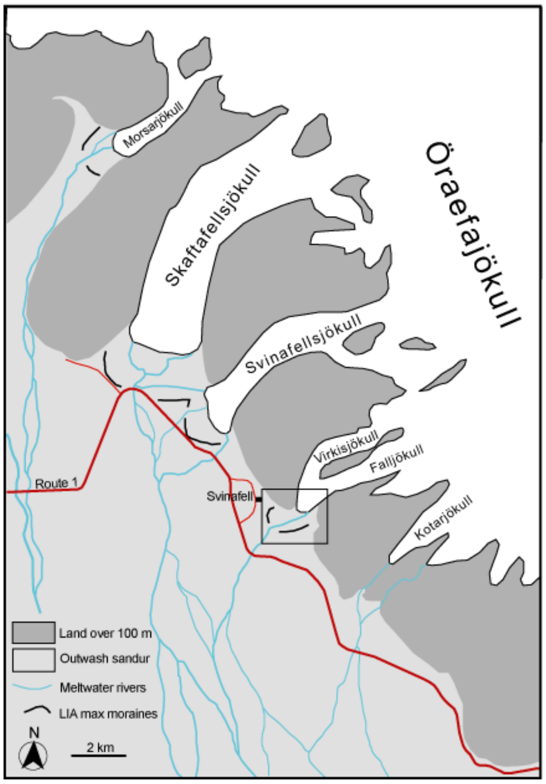
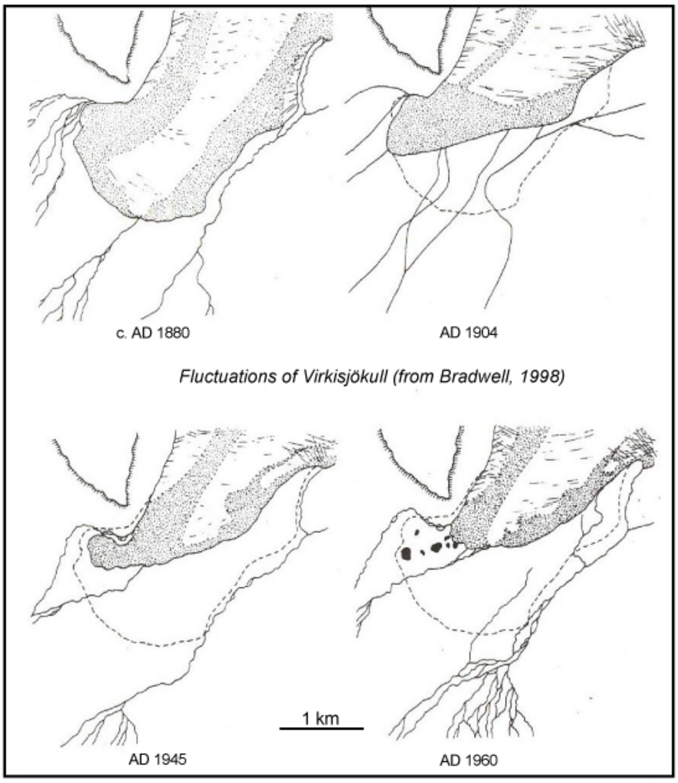
Eyles, N. 1979. Facies of supraglacial sedimentation on Icelandic and Alpine temperate glaciers, *Canadian Journal of Earth Sciences*, **16**: 1341-1361.

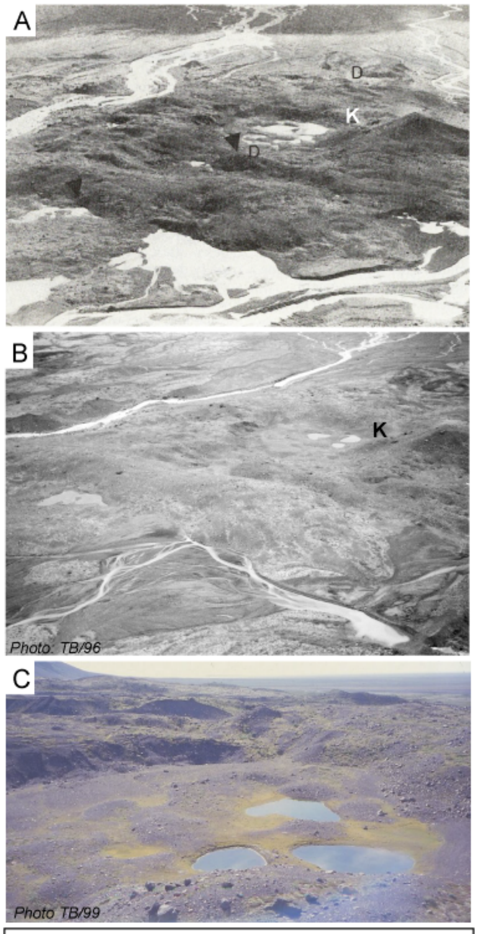
Eyles, N. 1983. Modern Icelandic glaciers as depositional models for hummocky moraine in the Scottish Highlands. In: E.B. Evenson, C. Schlüchter & J. Rabassa (Eds). *Tills and Related Deposits*, Balkema Press, Rotterdam.

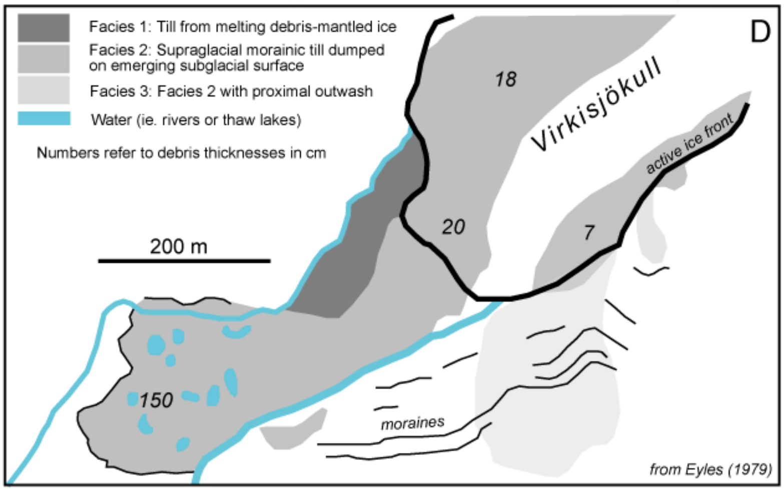
UNIT 11: VIRKISJÖKULL *Supraglacial debris and ice-stagnation topography*

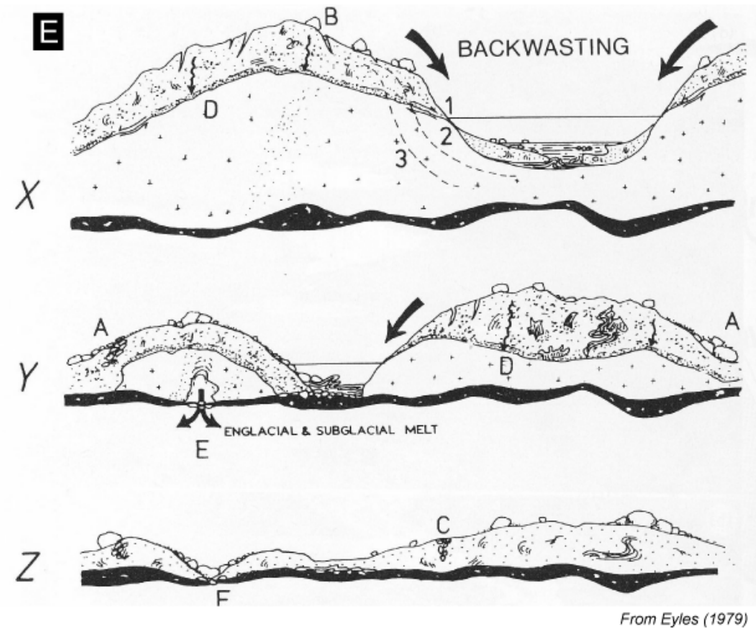




Fluctuations of Virkisjökull (from Bradwell, 1998)







A. Ice-stagnation topography, western Virkisjökull, July 1977 *(from Eyles, 1979)*. Note the large kettle hole complex (K).
B. Ice-stagnation topography, western Virkisjökull, July 1996, taken from same viewpoint. Note the small pools of water (K).
C. Kettle holes (K) containg sediment-laden meltwater (1999).
D. Facies of suraglacial sedimentation, Virkisjökull *(from Eyles, 1979)*.
E. Eyles' (1979) classic diagram of topographic inversion. The sequence **X**, **Y**, **Z**, shows backwasting of thaw lakes and kettle holes; slumping; gravity sorting and till inversion.

UNIT 12: VIRKISJÖKULL
Supra, sub and englacial debris

UNIT 12: VIRKISJÖKULL *Supra, sub and englacial debris*

Virkisjökull is a steep outlet glacier of the Öraefajökull ice cap with a collective catchment of ~15 km^2. The glacier drains from the summit of the volcano (2119m) and consists of two limbs that bifurcate around a central nunatak. A large medial moraine occurs at the confluence of the two ice flows. Debris covers the glacier to a depth of 0.5 m in places. A second zone of supraglacial debris occurs on the southern limb of the glacier. Numerous englacial debris bands exist in the terminal zone, several of these outcrop along the ice margin displaying basal-ice facies. Thick basal-ice facies are also exposed at the foot of the Falljökull ice cliff. Large areas of the glacier surface (c. 40%) are debris free.

The glacier foreland currently exhibits elements of 2 different landsystems which can be directly attributed to the nature and transport path of debris to the glacier margin: (i) glaciated valley; (ii) subglacial-proglacial. Facies of supraglacial sedimentation dominate the western half of the foreland; whilst landforms and sediments of subglacial deposition occur to the east of the river Virkisa (Eyles, 1979; 1983).

The **aims** of this unit are:

1. to recognise the range of sediments and landforms associated with supraglacial, subglacial and englacial debris supply to the glacier margin.

2. to examine the relative roles played by englacial and subglacial debris in landform generation.

3. to examine basal ice at the ice margin and the resultant sediment facies.

Research questions:

1. By what processes does debris accumulate along the ice margin of Virkisjökull?

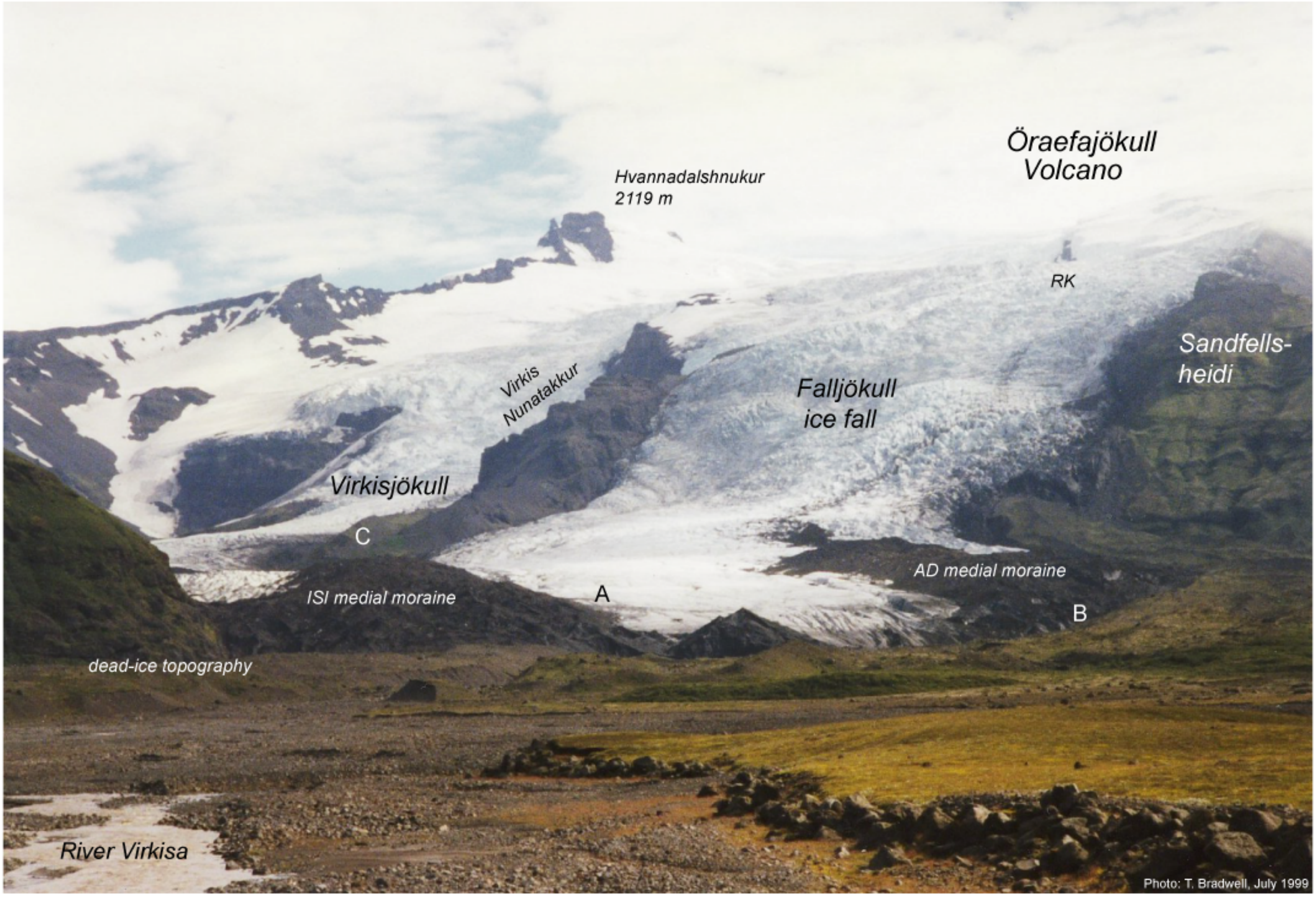
2. What are the relative roles played by pushing, dumping and englacial thrusting in the process of moraine formation?

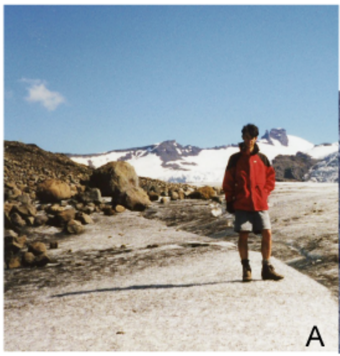
3. How have the superimposed moraine sequences formed and what are their relative ages?

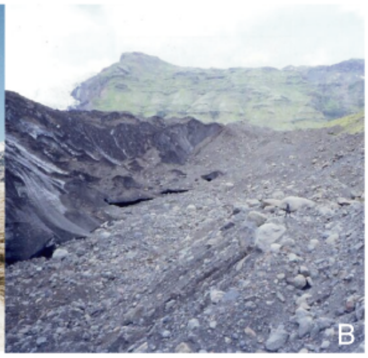
References:

Eyles, N. 1979. Facies of supraglacial sedimentation on Icelandic and Alpine temperate glaciers, *Canadian Journal of Earth Sciences*, **16**:1341-1361.

Eyles, N. 1983. Modern Icelandic glaciers as depositional models for hummocky moraine in the Scottish Highlands. In: E.B. Evenson, C. Schlüchter & J. Rabassa (Eds). *Tills and Related Deposits*, Balkema Press, Rotterdam.



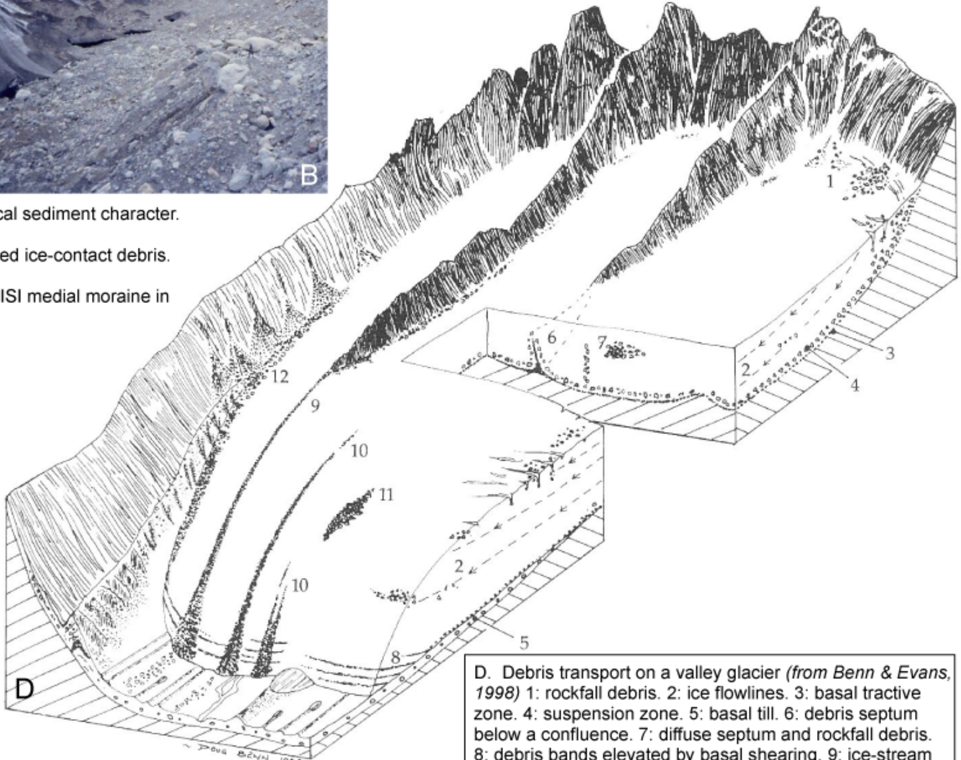




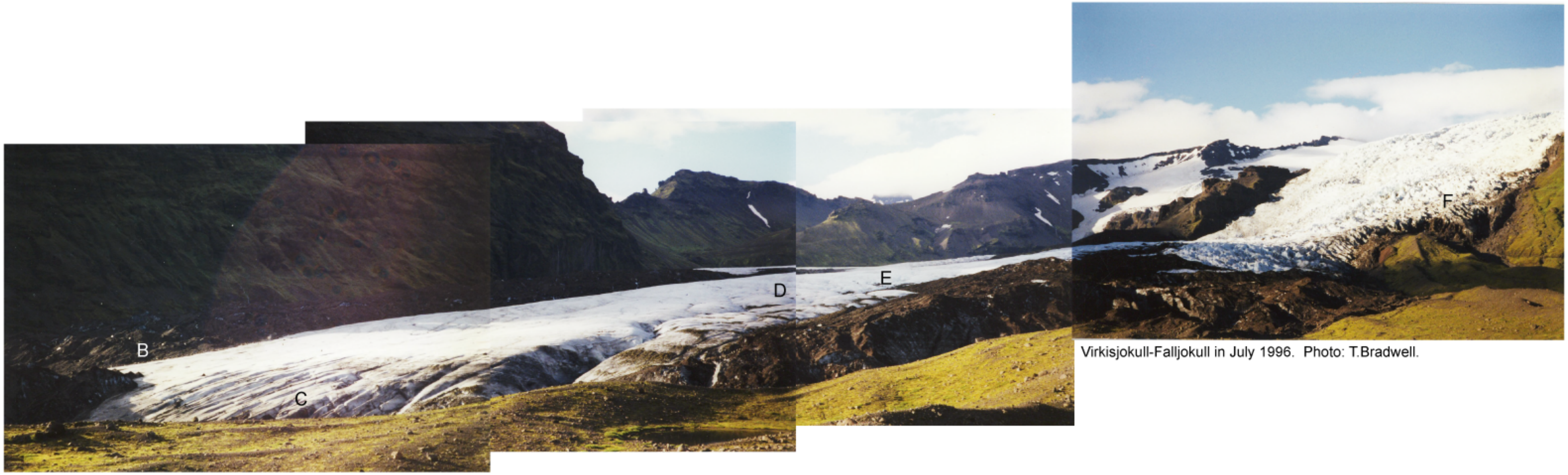
A. Margin of ISI medial moraine, showing typical sediment character.

B. Margin of AD medial moraine and associated ice-contact debris.

C. Lateral moraine on Virkis nunatakkur, with ISI medial moraine in the background (all photos: TB/96).



D. Debris transport on a valley glacier *(from Benn & Evans, 1998)* 1: rockfall debris. 2: ice flowlines. 3: basal tractive zone. 4: suspension zone. 5: basal till. 6: debris septum below a confluence. 7: diffuse septum and rockfall debris. 8: debris bands elevated by basal shearing. 9: ice-stream interaction (ISI) medial moraine. 10: ablation-dominant (AD) medial moraine. 11: avalanche-type medial moraine. 12: supra-glacial medial moraine.



Virkisjokull-Falljokull in July 1996. Photo: T.Bradwell.

B. Typical debris of the ice-stream interaction medial moraine on Virkisjokull. Poorly sorted sand, gravel, cobbles and boulders, many of which are angular or sub-angular, form a blanket of sediment on the glacier surface. This debris cover is >0.2 m thick in places and actively shields the under-lying ice from solar radiation. Photo: T.Bradwell, 1999.

C. Here the ice margin of Virkisjökull is relatively debris-free in places. Between the ISI and AD medial moraines is a section of the ice margin where englacial and subgacial debris transport dominate. Here the ice margin of Virkisjökull is relatively debris-free in places. The subglacial landsurface is being revealed with little modification from supraglacial debris. Occasional englacial debris bans outcrop at the ice amrgin. Supraglacial and englacial meltwater streams are actively removing and sorting debris along the ice margin. Photo: T.Bradwell, June 1999.

D. Englacial debris band out-cropping on the glacier surface in the ablation zone. Note the fine grade of the material and the ice axe for scale. Preserv-ation potential of such englac-ial debris features on the fore-land is low but may constitue a large percentage of sedim-ent supply to the margin. Photo: T.Bradwell, July 1999.

E. Isolated dirt cone in the ablation zone of Virkisjökull. Clean glacier ice has been shielded by a thin blanket of black tephra (<10 mm thick). Supraglacial dirt cones may grow to >1m in height before material is reworked by water or wind. The tephra may have originally been deposited an an englac-ial channel or crevasse. Note the ice axe for scale and the bands in the clean ice. Photo: T.Bradwell, July 1999.

F. Thick basal-ice facies seen at the foot of the ice fall, Falljökull. Debris is concentrated in bands and shear zones in the sole of the glacier. In places the debris content of the ice may exceed 50%. Large ice blocks have fallen from the margin in recent years, which can be examined in rela-tive safety. Note the person (circled) for scale. Photo: T.Bradwell, 1996.

UNIT 13: KOTARJÖKULL

Outwash fans: formation and incision

UNIT 13: KOTARJÖKULL *Outwash fans: formation and incision*

Kótarjökull is a small ice-fall glacier of the Öraefajökull ice cap. The glacier drains a high-altitude catchment c. 10 km^2 on the flank of the subglacial volcanic crater. The Kotá river has formed a sequence of well-defined terraces at the head of an extensive glaciofluvial outwash fan. The fan was deposited by debris-laden flood waters produced by the eruptions of Öraefajökull in AD 1362 and 1727. The extensive fan surface is littered with large blocks of palagonite tuff and lava that formed subglacially and were transported by high-energy flood waters during the more recent eruption (1727). Eyewitness accounts describe how in 1756 the fan was "still a terrible place covered by ice blocks, rocks, pumice and ash" (Thorarinsson, 1958). Large kettle holes, formed by melting ice blocks, occur across the eastern portion of the fan. Subsequent dissection of the outwash deposits occurred as the glacial river re-adjusted to the regional base level. Downcutting, totalling 29 m since the mid 18th century, has produced a flight of at least 8 erosional terraces. Attempts have been made to date these terraces through the use of lichenometry (Thompson & Jones, 1986).

The **aims** of this unit are:

1. to examine glaciofluvial outwash fans and terraces in proglacial environments.
2. to classify the sediment lithofacies associated with these deposits.
3. to examine the interplay between aggradation, incision and base-level change in dynamic glacial landscapes.

Research questions:

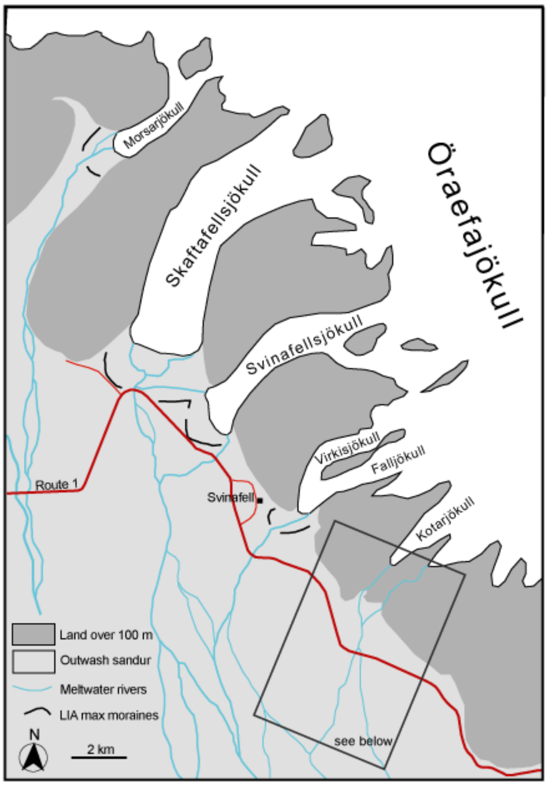
1. How valid is the chronology of fan deposition?
2. How do rates of channel incision relate to recession of the ice margin?
3. What are the implications of this case study for terrace sequences in formerly glaciated terrain (eg. Britain), particularly regarding the rate and mode of channel incision in unconsolidated sediments.

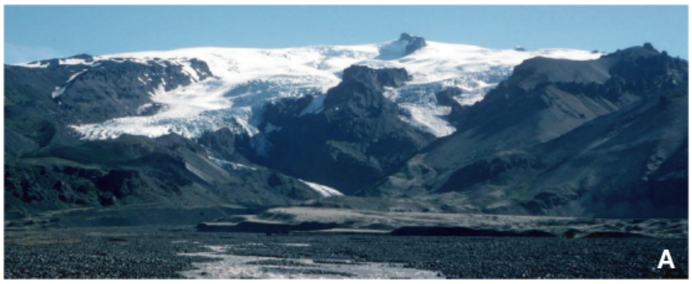
References:

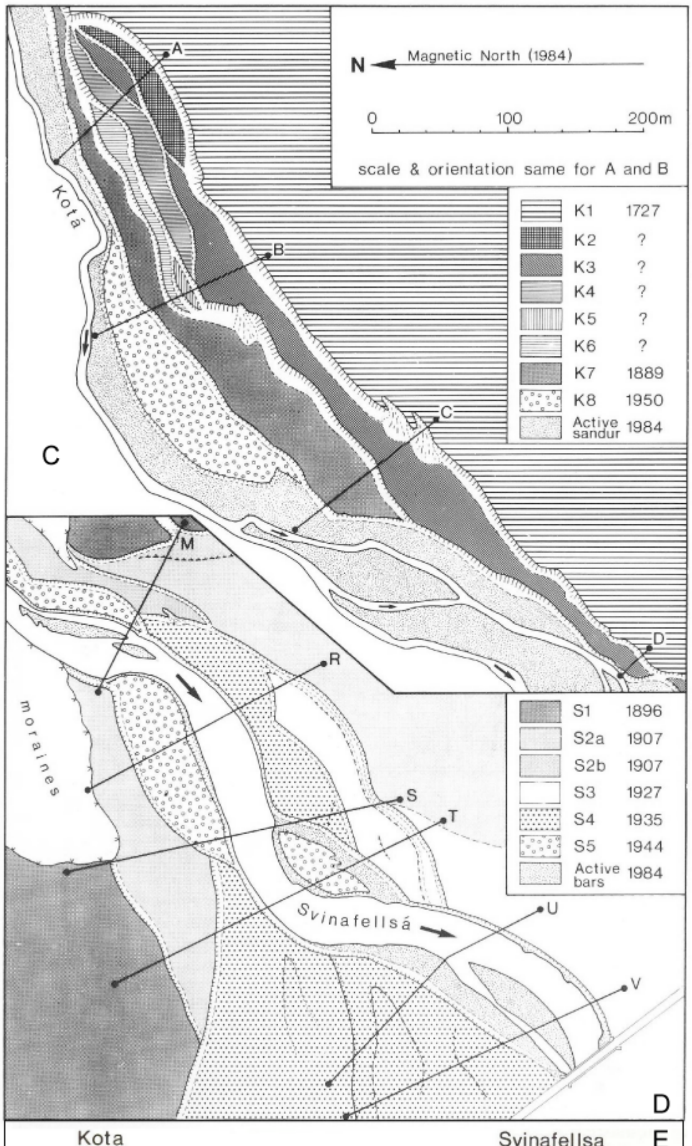
Thompson, A. and Jones, A. 1986. Rates and causes of proglacial river terrace formation in southwest Iceland: An application of lichenometric dating techniques. *Boreas*, **15**: 231-246.

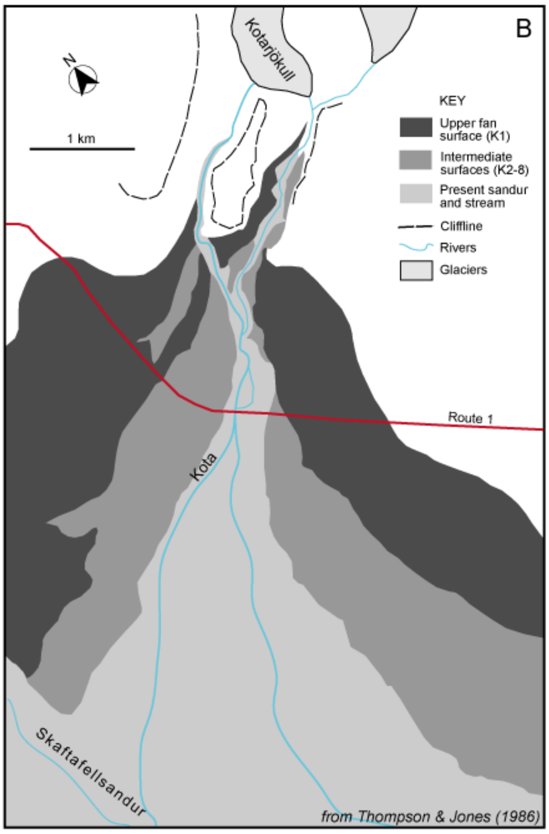
Thorarinsson, S. 1958. The Öræfajökull eruption of 1362. *Acta Nat. Isl.* II(2). Reykjavik, Náttúrufræðistofnun Islands.

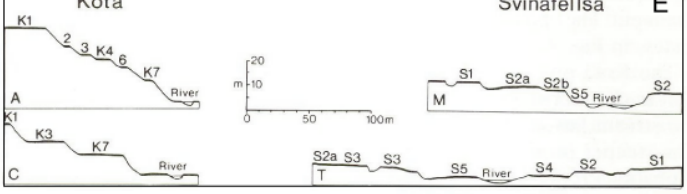
UNIT 13: KOTARJÖKULL *Outwash fans: formation and incision*











A. View of Kotarjökull from the lowest outwash fan surface. Note the terrace sequence in the middle distance (photo: J.W.Merritt, 1996).

B. The Kota outwash fan and terrace surfaces, mapped from aerial photographs *(from Thompson & Jones, 1986)*. The fan was deposited by flood water from Kotarjökull following eruptions in AD 1362 and 1727. The staircase of terraces has been formed by river incision since 1727.

C. Morphological maps of the Kota terraces *(from Thompson & Jones, 1986)*. The terraces were dated using lichenometry. Locations of profiles are indicated. Uncertainty surrounding the ages of certain terraces is due to lichen sampling problems and lack of suitable material for lichen growth.

D. Morphological maps of the Svinafellsa terraces *(from Thompson & Jones, 1986)*. All terraces have fomed since the Little Ice Age glacier maximum c. 1870, according to lichen dating. Rates of fluvial incision occurred in distinct phases, peaking in 1900-1920 and decreasing over the last 50 years.

E. Selected cross-profiles of terraces relating to the Kota and Svinafellsa rivers *(from Thompson & Jones, 1986)*.

UNIT 14: KVIARJÖKULL
Glaciated valley landsystem

UNIT 14: KVIARJÖKULL *Glaciated valley landsystem*

Kviarjökull is a small outlet glacier of the Öraefajökull ice cap. The glacier is sourced on the southern flanks of the Öraefi volcano, is 13 km long and currently drains an area c. 25km^2. The glacier falls steeply in its upper reaches and more gradually in its ablation area. Kviarjökull is assumed to be temperate throughout and flows in an overdeepened trough (Björnsson, 1979; Spedding & Evans, 2002). The glacier is notable for its extremely large termino-lateral moraine complex. During the Little Ice Age maximum, c.1850, the glacier terminus reached the top of the moraine ramparts, according to eye-witnesses, dry-calving ice blocks onto the sandur below (Thorarinsson, 1943).

The glacier was identified by Eyles (1979, 1983) as an exemplar of the *glaciated valley* landsystem. The high degree of supraglacial (rockfall) debris and passive transportation, coupled with the low degree of lodgement processes and meltwater transportation, suggest it is typical of alpine-type glaciation. However, recently, Spedding and Evans (2002) argued that Eyles (1979) "played down" the role of alternative transport pathways at Kviarjökull. Based on detailed sediment studies they attribute the large ramparts to the high-debris turnover and dynamic drainage network associated with a glacier occupying an unusually overdeepened basin. Kviarjökull has also been suggested as a locality for glaciohydraulic supercooling, although sedimentary evidence remains equivocal (Swift *et al*., 2005).

The **aims** of this unit are:

1. to recognise the range of sediments and landforms associated with the glaciated valley landsystem.
2. to describe sediments along the margin of an alpine-type valley glacier.
3. to examine the evidence for fluvial reworking in the glacier terminus zone.

Research questions:

1. What is the likely transport mode of the sediments at the glacier margin and how do they relate to the competing models of Eyles (1979) and Spedding & Evans (2002).
2. Why are the lateral moraines at Kviarjokull so exceptionally large?
3. What is the evidence for supercooling at the ice margin?

References:

Björnsson, H. 1979. Glaciers in Iceland. *Jökull*, **29**: 74-80.

Eyles, N. 1979. Facies of supraglacial sedimentation on Icelandic and Alpine temperate glaciers, *Canadian Journal of Earth Sciences*, **16**: 1341-1361.

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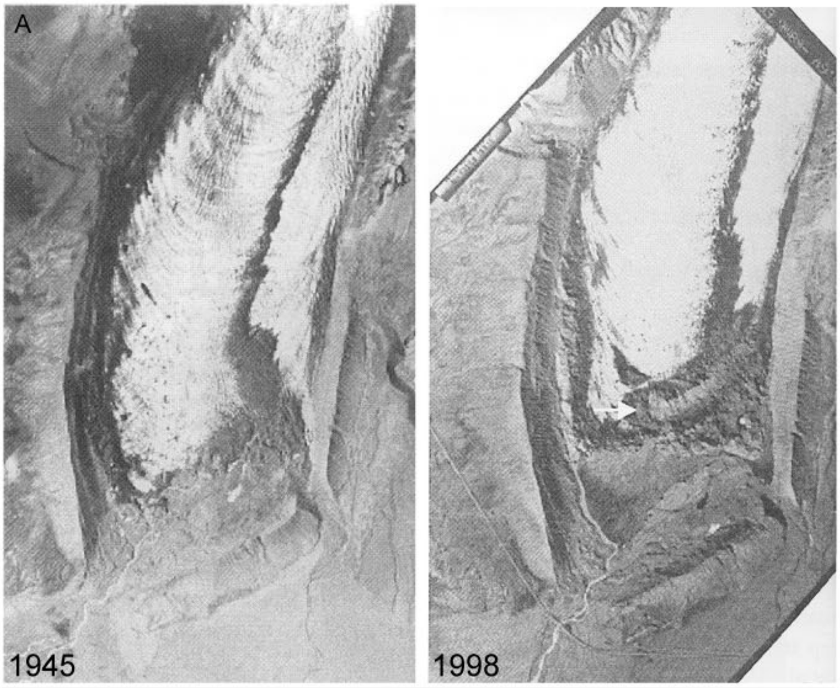
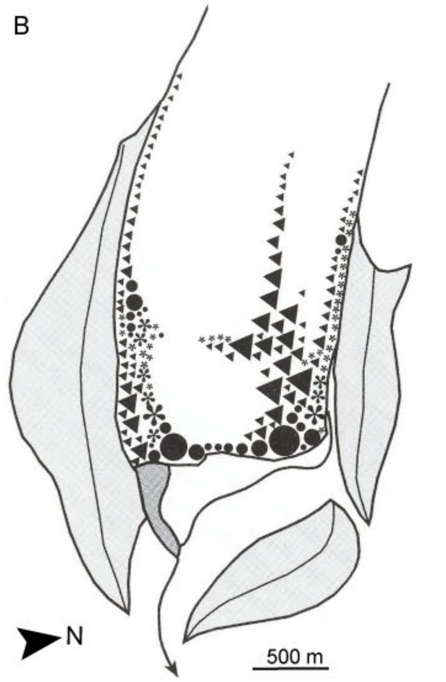
Thorarinsson, S. 1943. Vatnajökull: Scientific results of the Swedish-Icelandic investigations 1936-37-38. Chapter XI: Oscillations of the Iceland glaciers in the last 250 years. *Geografiska Annaler*, **1-2**: 1-54.

UNIT 14: KVIARJÖKULL *Glaciated valley landsystem*





A. Aerial photographs of Kviarjökull (National Land Survey of Iceland). Approximate scale 1:40,000. Note the large lateral moraine ramparts, medial moraine and extensive debris cover on the snout. The glacier margin thinned considerably, but retreated only c. 250m, during the intervening period.

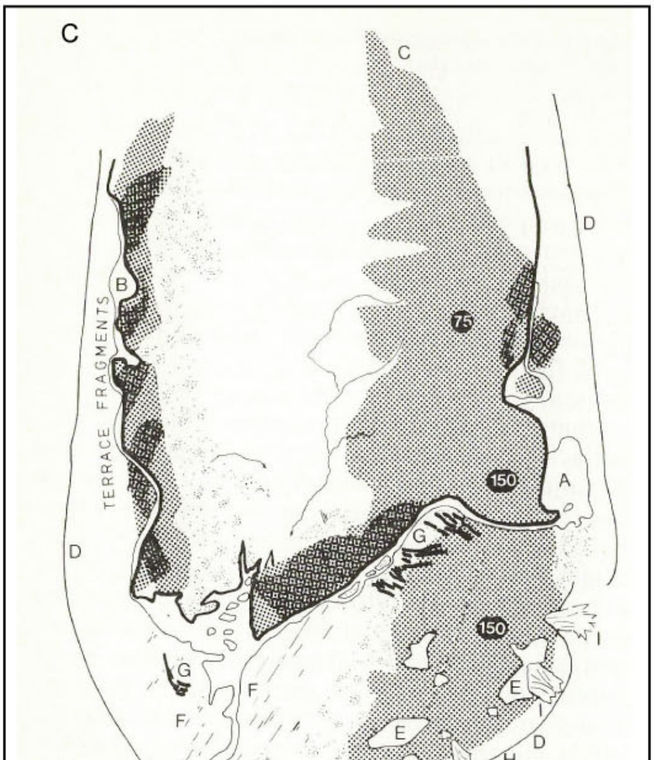
C. (below) Facies of supraglacial debris and till at Kviarjökull *(from Eyles, 1979)*. Facies 1 extends down valley as an ice-cored zone directly deposited from the medial moraine. Facies 2 includes fluted lodgement till and push moraines. Facies 3 accumulates along meltwater streams. Numbers refer to supraglacial debris thickness in cm. See Unit 11 for facies definitions.

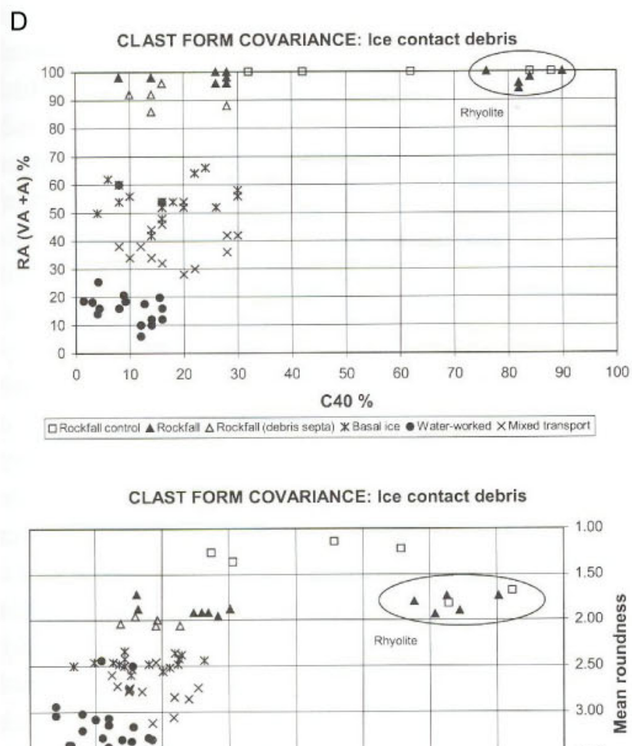
D. (right) Clast form covariance plots for ice-contact debris *(from Spedding & Evans, 2002)*.

B. Sketch map of glacier terminus showing distribution of 3 principal debris types *(from Spedding & Evans, 2002)*

- ◀ rockfall debris
- * basal ice and debris
- ● water-worked ('relict channel fill') debris from englacial debris bands

Shaded areas are moraine ramparts





UNIT 15: KVIARJÖKULL
Dating controversy

UNIT 15: KVIARJÖKULL *Dating controversy*

Kviarjökull, at the southeastern tip of Öraefajökull, is a high-turnover outlet glacier in an extremely maritime setting. The glacier receives between 4 and 8 m precipitation a year and terminates at 20 m above sea level. The glacier has been the focus of several dating studies over the last 50 years.

Thorarinsson (1956) studied tephras in soil profiles on the large lateral ramparts to deduce the minimum age of the moraine complex. He found the moraines to be at least 2000, but probably but not more than 6000, years old. Black (1990) and Gudmundsson (1998) used radiocarbon and tephra layers to date early- and mid-Holocene advances at Kviarjökull. Evans *et al.* (1999) used lichenometry to date moraines at Kviarjokull as part of a wider study. Evans *et al's* results suggested that all the moraines date from the late 19th and early 20th centuries – a result clearly at odds with the tephrastratigraphical evidence. This study merely serves to highlight the risks of applying an inappropriate dating tool and ignoring the multi-proxy approach. Recently, Bradwell (2004) found the age of the large moraines at Kviarjökull and neighbouring Holarjökull to be beyond the limits of the lichenometric technique (>600 yrs BP). This work also found that the crest of the moraines had been re-occupied in the LIA (c. 1850) and that deglaciation since ~1900 had been in the form of punctuated rapid retreat.

The **aims** of this unit are:

1. to recognise the applicability of various dating techniques in recently glaciated terrain.
2. to critically examine the evidence for pre-Little Ice Age glacier fluctuations in Iceland.
3. to discuss the implications of moraine-dating studies in a wider context.

Research questions:

1. What do the results of Evans *et al*'s lichenometric dating actually mean?
2. What are the limitations of other dating techniques used in recently glaciated terrain (eg. C-14, OSL, tephra, etc.)
3. Are glacier fluctuations at Kviarjökull and Holarjökull representative of climatic change throughout the Holocene?

References:

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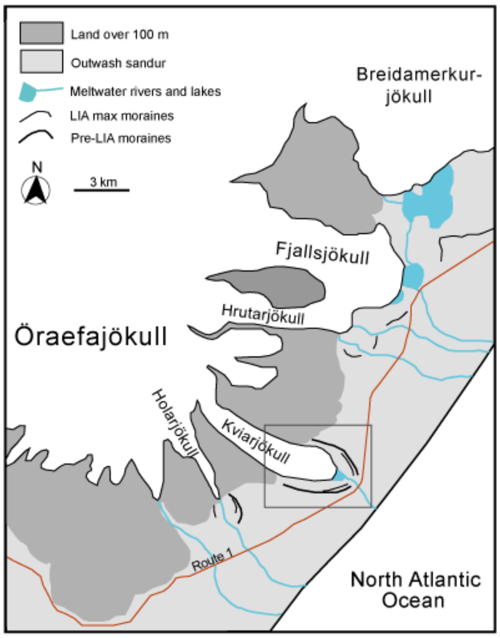
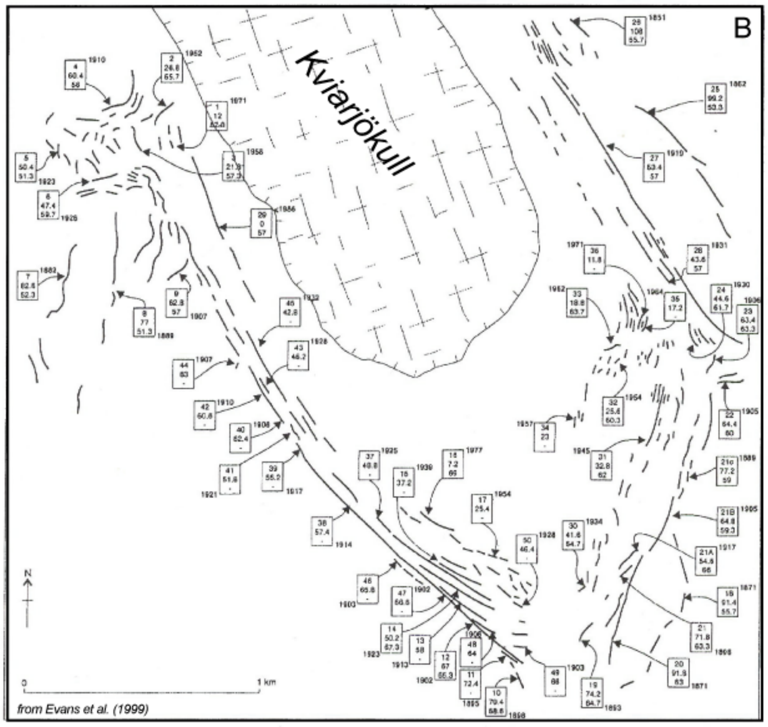
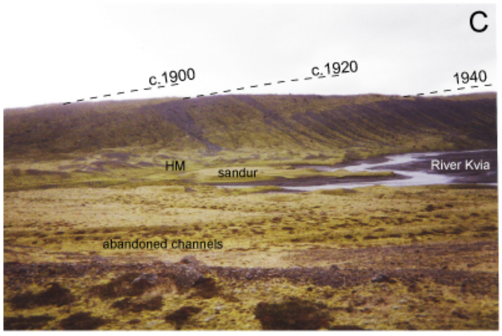
UNIT 15: KVIARJÖKULL

Dating controversy



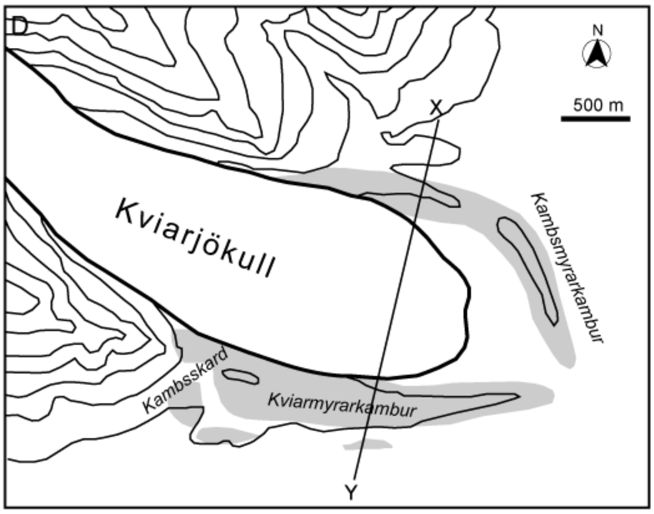


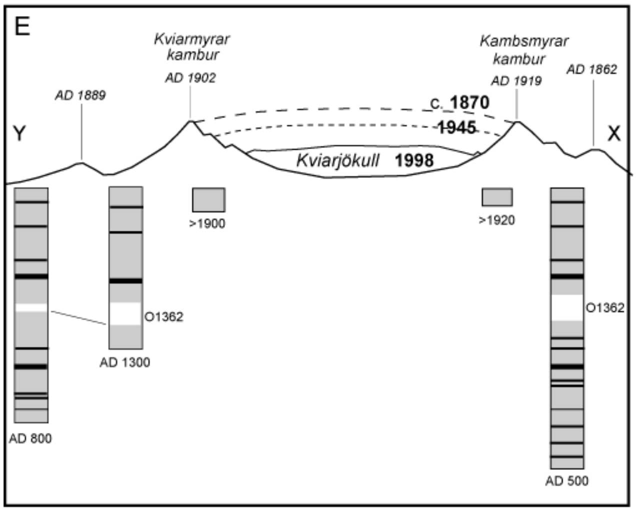


A. Looking west along the large lateral moraine at Kviarjökull. Note the debris-covered glacier margin (photo: J.W. Merritt, 1996).

B. Moraines at Kviarjökull and their relevant lichenometric ages. Ages are in years AD and were calculated using a linear growth rate of 0.80 mm/a *(from Evans et al., 1999)*.

C. View across the glacier foreland towards the eastern lateral-moraine rampart. Note the 20th-century recessional limits on the lateral moraine slope and the hummocky moraines (HM) formed by small-scale pushing and fluting of pre-existing proglacial sediments (photo: T.Bradwell, 1999).





D. Kviarjökull's very large termino-lateral moraine complex forms a horse-shoe shaped amphitheatre c.100m high and 1000m wide. Moraines shown in grey; contours at 100m vertical intervals.
E. Cross section of the terminus of Kviarjökull along the line X-Y (see D) *(modified from Thorarinsson, 1956)*. The position of the ice margin is shown at various times since the LIA maximum; dates in **bold** are from eye-witness accounts or aerial photographs. Soil profiles recorded by Thorarinsson (1956) are also shown; minimumum age of soil according to tephrostratigraphy below each profile. Dates in *italics* are from *Evans et al's, (1999)* lichenometric study.

UNIT 16: FJALLSJÖKULL

Subglacial processes and annual moraines

UNIT 16: FJALLSJÖKULL *Subglacial processes and annual moraines*

Fjallsjökull is a medium-sized, piedmont, outlet glacier draining the north-eastern flanks of Öraefajökull. The glacier is c.12 km long and 3 km wide; its terminus formerly coalesced with Breidamerkurjökull to the north and Hrutarjökull to the south. The glacier reached its Little Ice Age maximum in ~1850, according to Thorarinsson (1943), or in the 1780s, according to Bradwell (2004a). Fjallsjökull retreated considerably during the 20^{th} century and has been monitored by local farmers since 1930. Price (1970) studied moraines and outwash deposits and proposed a model of proglacial landscape evolution. The foreland is famous for its well-preserved moraine sequences recording minor, often annual, fluctuations of the ice margin. Many of these formed between 1930 and 1960 when the glacier experienced an unbroken run of negative mass balance years. Other annual moraine sequences can be seen at the neighbouring glaciers of Breidamerkurjökull (Boulton, 1986), Skalafellsjökull (Sharp, 1984), and Lambatungnajökull (Bradwell, 2004b). Most annual moraines form by the squeezing of wet deformable sediment from beneath the glacier terminus during small winter-spring advances (Sharp, 1984; Kruger, 1995).

The **aims** of this unit are:

1. to recognise the range of sediments and landforms found in a subglacial-proglacial landsystem.
2. to understand the processes of till deposition and annual moraine formation.
3. to examine the evidence for a deformable layer beneath the glacier margin.

Research questions:

1. What are the main processes of subglacial sediment transportation and deposition?
2. What is the significance of clasts with 'stoss-lee' forms on the glacier foreland?
3. How can the moraines at Fjallsjökull be used as a climate proxy?

References:

Boulton, G.S. 1986. Push moraines and glacier contact fans in marine and terrestrial environments. *Sedimentology*, **33**: 677-698.

Bradwell, T. 2004a. Annual moraines and summer temperatures at Lambatungnajökull, Iceland. *Arctic, Antarctic and Alpine Research*, **36**: 601-607.

Bradwell, T. 2004b. Lichenometric dating in southeast Iceland: the size-frequency approach. *Geografiska Annaler*, **86A**: 31-41.

Kruger, J. 1995. The origin and climatological significance of push moraines, Myrdalsjökull, Iceland. *The Holocene*, **5**: 420-427.

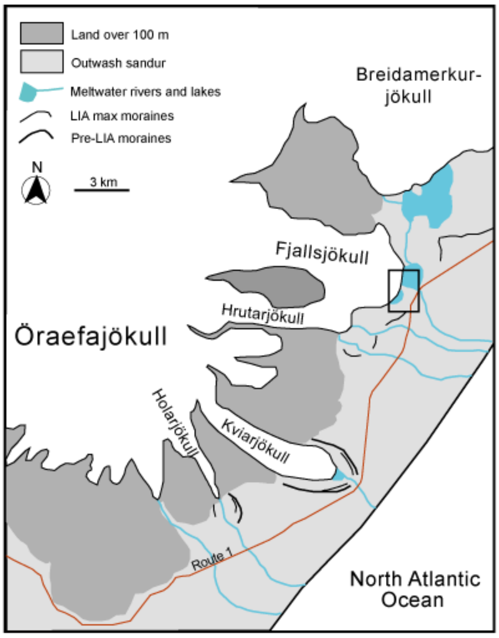
Price, R.J. 1970. Moraines at Fjallsjökull, Iceland. *Arctic and Alpine Research*, **2**: 27-42.

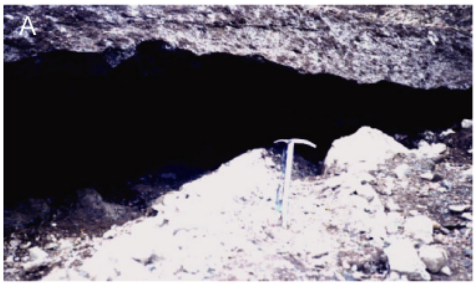
Sharp, M. 1982. Modification of clasts in lodgement tills by glacier erosion. *Journal of Glaciology*, **28**, 475-481.

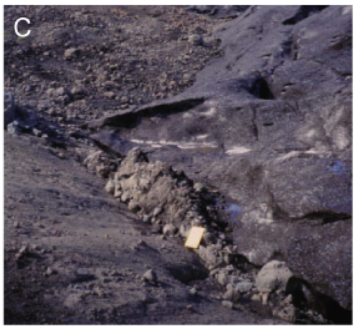
Sharp, M. 1984. Annual moraine ridges at Skálafellsjökull, south-east Iceland. *Journal of Glaciology*, **30**: 82-93.

Thorarinsson, S. 1943. Vatnajökull: Scientific results of the Swedish-Icelandic investigations 1936-37-38. Chapter XI: Oscillations of the Iceland glaciers in the last 250 years. *Geografiska Annaler*, **1-2**: 1-54.

UNIT 16: FJALLSJÖKULL *Subglacial processes and annual moraines*



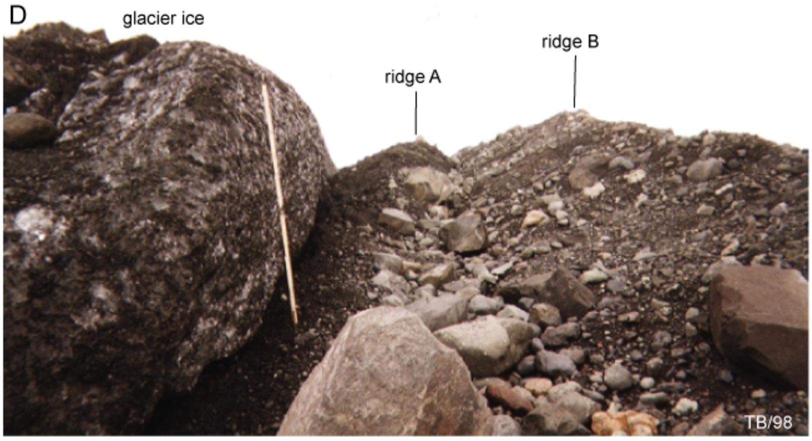


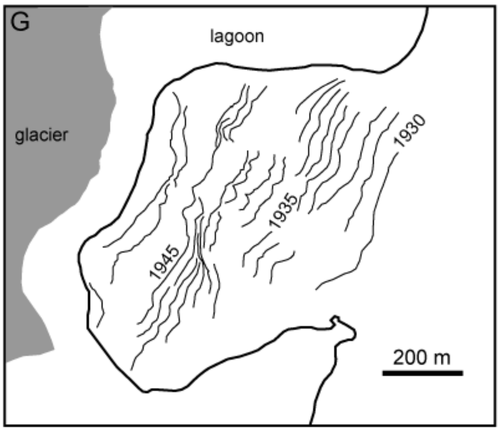


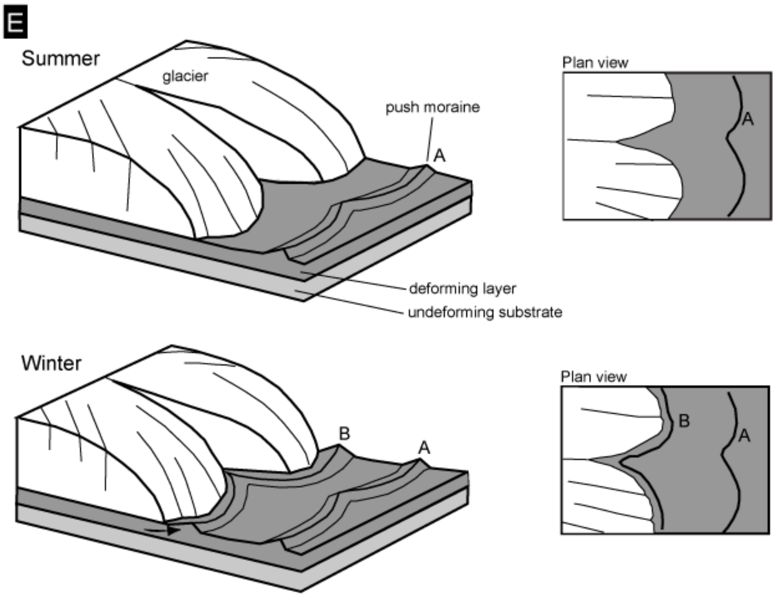
A. Small flute of subglacial debris emerging from the margin of Fjallsjökull. Photo: T.Bradwell, May 1999.

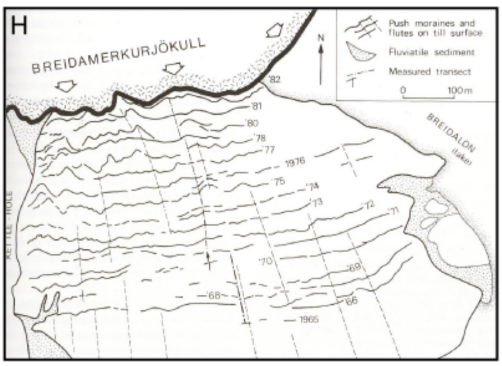
B. Large degraded flute in the lee of a lodged boulder, foreland of Breidamerkurjökull. Ice flow away from the viewer. Photo: D.Evans,1995.

C. 'Micro moraine' formed by a combination of squeezing of subglacial sediment and pushing of ice-marginal debris. Ridges of this type can form during seasonal fluctuations of the ice margin when wet sediment is extruded from beneath the advancing glacier terminus. Note logbook for scale. Photo: T.Bradwell, May 2001.









D. Minor push moraines forming at the margin of Fjallsjökull. Soft defomable sediment is squeezed from beneath the toe of the glacier duing small advance events. Ridge A is actively forming; ridge B probably fromed the previous winter or spring. Note the metre stick for scale. Photo taken May 1998.
E. Schematic of annual moraine formation by squeezing or extrusion of subglacial deforming layer. This model was originally proposed by *Sharp (1984)*. Note how the moraine morphology mirrors the outline of the crevassed ice margin. *Modified from Bradwell (2001)*.
F. Sequence of annual moraines preserved on the foreland at Fjallsjökull.
G. Outline map of moraine morphology with dates of formation, deduced from aerial photographs.
H. Annual moraines, with formation ages, on the foreland of Breidamerkurjökull, *from Boulton, 1986*.

UNIT 17: JÖKULSARLON
Proglacial lakes

UNIT 17: JÖKULSARLON *Proglacial lakes*

Jökulsarlon, an iceberg-filled proglacial lake, first appeared in 1933 following the retreat of Breidamerkurjökull, a large outlet glacier of southeastern Vatnajökull. The glacier reached its Little Ice Age maximum extent in the late 19^{th} century Since then the lake has grown to 15 km^2 at the end of the 20th century, as a result of the continuing retreat of the Breidamerkurjökull margin (Evans and Twigg, 2002).

Sedimentation in the lake takes place by a number of mechanisms (Boulton *et al.*, 1982; Björnsson *et al.*, 2001). The role of debris-laden subglacial meltwater is probably the most significant. Fan-delta complexes form both subaqueously and, dependent on lake level, subaerially at the margin. At Jökulsarlon grounding line fans dominate the subaqueous margin, as the ice front is rapidly calving. Transport of supraglacial and englacial debris takes place through the transit and melting of icebergs across the lake.

The **aims** of this unit are:

1. to examine a fine example of a proglacial lake and the associated landform-sediment assemblages.

2. to recognise the role of icebergs in the transport of glacial debris.

3. to understand the interplay between glacier retreat and the creation of long-lived proglacial lakes.

Research questions:

1. Why has a particularly deep proglacial lake been created at this point on the margin of Breidamerkurjökull?

2. How can the evolution of this lake system tell us more about the wider palaeoenvironment?

3. To what extent can we expect to find similar diagnostic landsystem elements in the British Quaternary record?

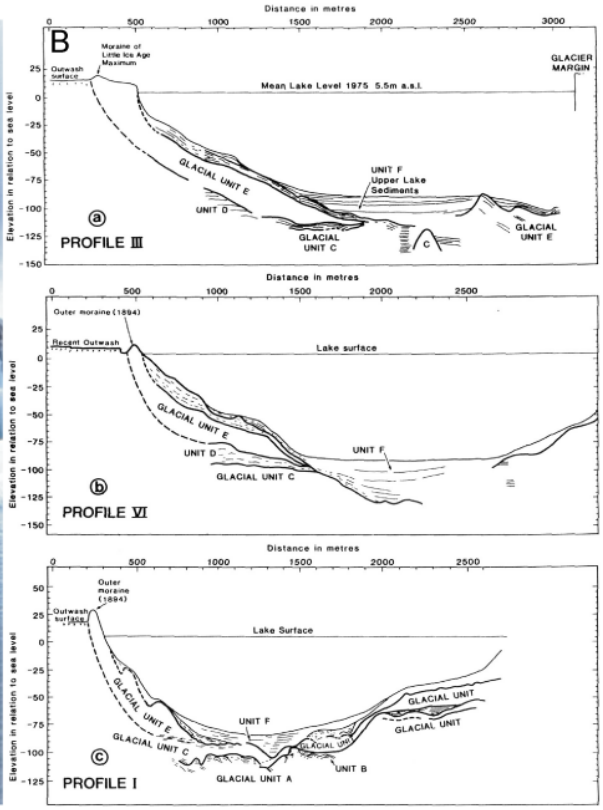
References:

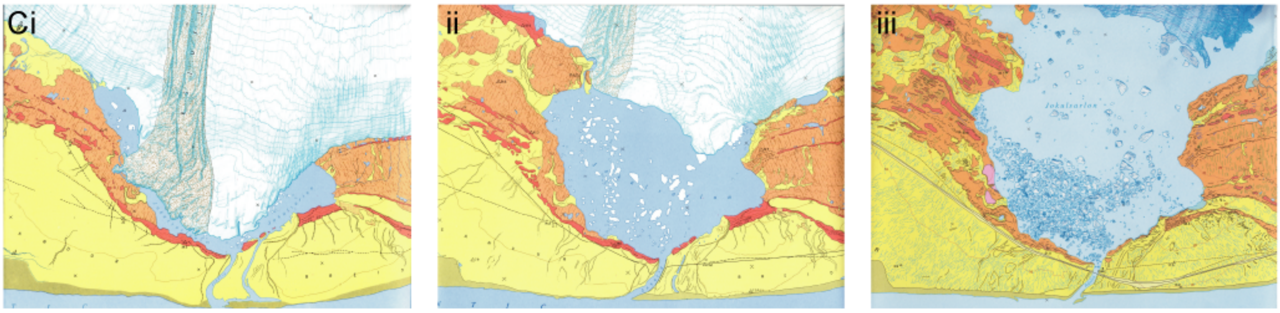
Boulton, G.S., Harris, P.W.V. and Jarvis, J. 1982. Stratigraphy and structure of a coastal sediment wedge of glacial origin inferred from sparker measurements in glacial Lake Jökulsarlon in southeastern Iceland. *Jökull*, **32**: 37-47.

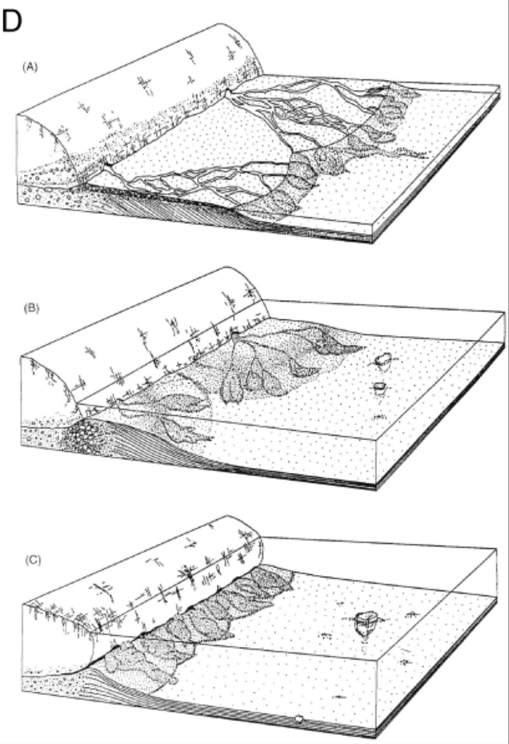
Björnsson, H., Palsson, F. and Gudmundsson, S. 2001. Jökulsarlon at Breidamerkursandur, Vatnajökull, Iceland: 20th century changes and future outlook. *Jökull*, **50**: 1-18.

Evans, D.J.A. and Twigg, D. R. 2002. The active temperate glacial landsystem: a model based on Breidamerkurjokull and Fjallsjokull, Iceland. *Quaternary Science Reviews*, **21**: 2143-2177

UNIT 17: JÖKULSARLON *Proglacial lakes*







A. Blue icebergs in Jökulsarlon proglacial lagoon. These bergs calve from the margin of Breidamerkurjökull, which terminates at the northern margin of the lake.

B. Interpretations of Sparker traverse records (Boulton *et al.* 1982) showing inferred stratigraphy of Jökulsarlon bed.

C. A series of maps produced by *Landmaelingar Islands* and the University of Glasgow charting the recession of Breidamerkurkerjokull over the last 60 years.

i. 1945: Breidamerkurjökull's margin is within 1km of the coast. The lobe of ice carrying the glacier's main medial moraine, is surrounded by a series of small lakes.

ii. 1965: The ice lobe has undergone significant retreat northwards, opening up the lake. Recession is accelerated in the lake, most likely due to increased calving as the thinning glacier margin decouples from the lake floor.

iii. 1998: Further retreat increases the size of the lagoon. Retreat rates begin to normalise across the whole glacier margin.

D. Three possible types of sedimentation in a lake at the margin of an ice sheet or large glacier.

a. Gilbert-type delta complex fed by subglacial conduits, showing subaerial alluvial topsets and steeply dipping foreset beds, that merge with bottomset beds in deeper water.

b. Subaqueous fan-delta lobes fed by subglacial conduits; avalanching and mass movement dominate; sedimentation away from the ice margin is mainly from density underflow currents.

c. Subaqueous fan apron in deep water fed by numerous conduits linked by a subglacial cavity system; the complex of rapidly deposited fluvial sediment and diamicton from the ice is commonly called a grounding-line fan.

UNIT 18: HEINABERGSJÖKULL
Ice-dammed lakes

UNIT 18: HEINABERGSJÖKULL *Ice-dammed lakes*

Heinabergsjökull is a medium-sized outlet of southern Vatnajokull. The glacier was formerly more extensive and in the 19th century coalesced with neighbouring Skalafellsjökull to form a broad piedmont lobe (Thorarinsson, 1943). This glacial configuration impounded water in the 7km-long ice-free valley of Heinabergsdalur. This lake – Dalvatn – persisted until the 1920s, when the glacier became too thin to act as a dam. Dalvatn drained in several outburst floods (jökulhlaups) which cut a series of terraces in pre-existing sandur deposits. The lake has left a fossil record of glaciolacustrine sedimentation in the form of deltas, fans, lake terraces, depositional shorelines and beach deposits (Bennett *et al*., 2000). The sedimentology is dominated by ice-rafted deposits and matrix-rich gravels. Soft-sediment deformation, liquefaction and iceberg grounding structures are also in evidence. Some of the palaeo-lake shorelines have been dated through the use of lichenometry (Evans *et al*., 1999). A small ice-dammed lake currently exists at the margin of Heinabergsjökull, in upper Heinabergsdalur (c.400 m asl). This lake – Vatnsdalur – also has a history of catastrophic drainage.

The **aims** of this unit are:

1. to recognise the landform-sediment assemblage associated with ice-dammed glacier lakes.

2. to examine the modern lithofacies associations and relate these to processes operating in glaciolacustrine environments.

3. to examine evidence relating to catastrophic lake drainage events (jökulhlaups)

Research questions:

1. What is the link between former lake shorelines and fluctuations of the ice margin?

2. Can we relate facies architecture to changes in water depth, iceberg calving and lake drainage events?

3. How does the geomorphology and sedimentology in Heinabergsdalur relate to fossil examples of ice-dammed lakes in Britain?

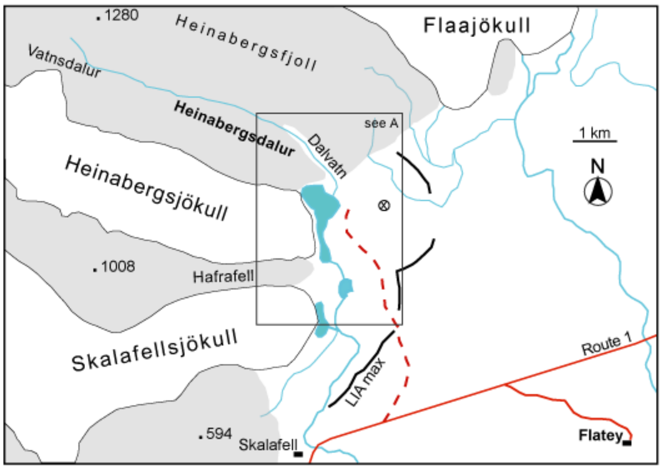
References:

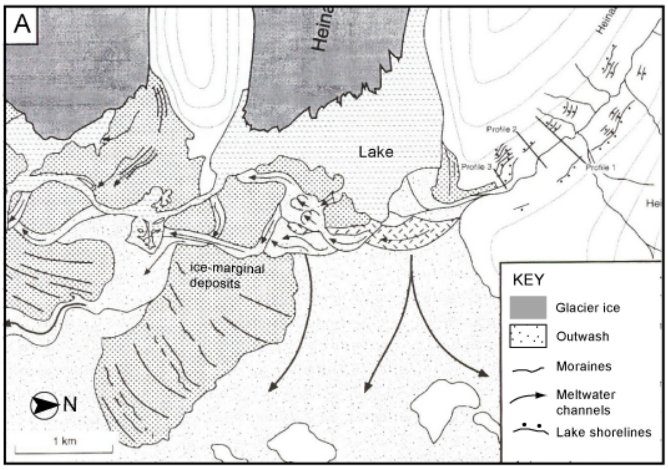
Bennett, M.R., Huddart, D. and McCormick, T. 2000. The glaciolacustrine landform-sediment assemblage at Heinabergsjökull, Iceland, *Geografiska Annaler*, **82A**: 1-16.

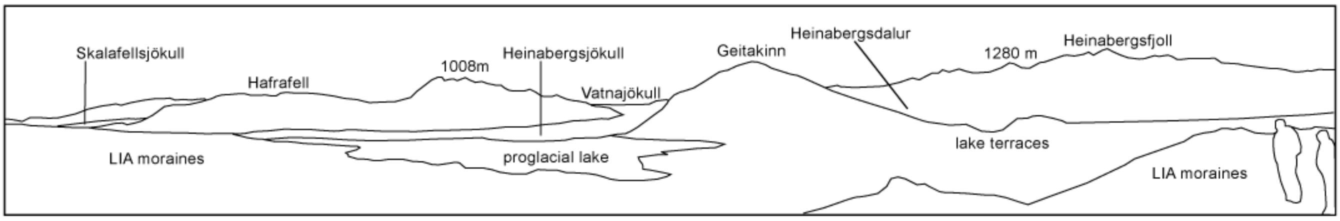
Evans, D.J.A., Archer, S. & Wilson, D.J.H. 1999. A comparison of the lichenometric and Schmidt hammer dating techniques based on data from the proglacial areas of some Icelandic glaciers. *Quaternary Science Reviews*, **18**: 13-41.

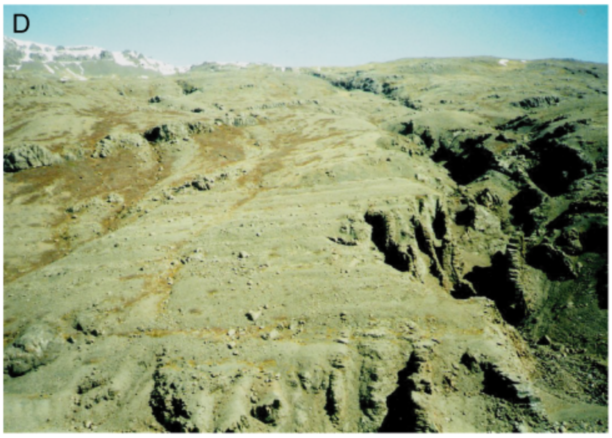
Thorarinsson, S. 1943. Vatnajökull: Scientific results of the Swedish-Icelandic investigations 1936-37-38. Chapter XI: Oscillations of the Iceland glaciers in the last 250 years. *Geografiska Annaler*, **1-2**: 1-54.

UNIT 18: HEINABERGSJÖKULL *Ice-dammed lakes*









A. Geomorphological map of the former ice-dammed lake in Heinabergsdalur *(from Bennett et al., 2000)*. At least 8 palaeo-lake shorelines have been identifed. They are composed of depositional terraces reworked from valley-side colluvium, and are best developed near the valley entrance (SW side).
B. 180° panorama of the foreland of Heinabergsjökull. The lake terraces relate to when the glacier was considerably more extensive and dammed water in Heinabergsdalur, prior to c.1920. Photo taken from the x on location map. Outline sketch shows simplified geographical features.
C. Dissected sequence of glaciofluvial terraces associated with the former lake in Heinabergsdalur (photo: A.Casely, 2001).
D. Staircase of erosional lake shorelines in bedrock and slope deposits, N side of Heinabergsdalur (photo: A.Casely, 2001).
E. Modern ice-dammed lake (Vatnsdalur) at N end of Heinabergsdalur. Note the highly crevassed margin of Heinabergsjökull and the flotilla of ice bergs.

UNIT 19: SKALAFELLSJÖKULL
Lithofacies analysis

UNIT 19: SKALAFELLSJÖKULL *Lithofacies analysis*

Skalafellsjökull is a medium-sized outlet glacier of the Vatnajökull ice cap. The glacier is sourced on the Breidabunga subglacial massif and drains around 100km^2 of the southeast portion of the ice cap. During the Little Ice Age maximum the glacier terminus was coalescent with Heinabergsjökull to the north forming a broad piedmont lobe. The exact timing of this event is still debated (Thorarinsson, 1943; Evans *et al*., 1999, McKinzey *et al*., 2004). The glacier margins separated in the 1920s according to historical accounts and lichenometric evidence. The glacier foreland at Skalafellsjökull exhibits a wealth of subglacially and proglacially generated landforms. These have been mapped in detail by Gordon & Sharp (1983) and Evans *et al*. (1999). Of particular note is the well-preserved sequence of annual moraines, described by Sharp (1984) in his now-classic study.

The evolution of the sandur at Skalafellsjökull has been rapid, particularly since the separation of the two glacier fronts (see Unit 18), with the main meltwater rivers shifting course several times in recent decades. Abandoned channels have left numerous good sections through proglacial sediment sequences. This unit will concentrate on unravelling the sequence of events preserved in one of these sections.

The **aims** of this unit are:

1. to recognise the range of sediments and landforms found on a modern glacier foreland.

2. to describe and analyse the lithofacies associations of a large gravel-diamict section in a contemporary glacial environment.

3. to discuss the likely mode of origin of these sediments and reconstruct the sequence of events.

Research questions:

1. What is the evidence for subglacial deformation on the foreland of Skalafellsjökull?

2. How applicable is lithofacies association analysis in describing sediments from ancient glacial landscapes?

3. What are the main geomorphic agents of landscape evolution adjacent to modern glaciers?

References:

Evans, D.J.A. 2000. A gravel outwash/deformable till continuum, Skálafellsjökull, Iceland. *Geografiska Annaler*, **82A**: 499-512.

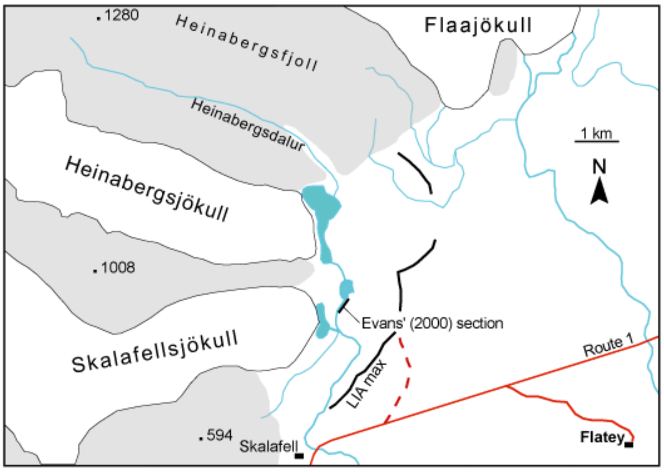
Evans, D.J.A., Archer, S. and Wilson, D.J.H. 1999. A comparison of the lichenometric and Schmidt-hammer dating techniques based on data from the proglacial areas of some Icelandic glaciers. *Quaternary Science Reviews*, **18**: 13-41.

Gordon, J.E. and Sharp, M. 1983. Lichenometry in dating recent glacial landforms and deposits, southeast Iceland. *Boreas,* **12**: 191-200.

McKinzey, K., Orwin, J., Bradwell, T. 2004. Re-dating the moraines at Heinabergsjökull and Skalafellsjökull using different lichenometric methods: implications for the timing of the Icelandic Little Ice Age maximum. *Geografiska Annaler*, **86A**: 319-336.

Sharp, M. 1984. Annual moraine ridges at Skálafellsjökull, south-east Iceland. *Journal of Glaciology*, **30**: 82-93.

Thorarinsson, S. 1943. Vatnajökull: Scientific results of the Swedish-Icelandic investigations 1936-37-38. Chapter XI: Oscillations of the Iceland glaciers in the last 250 years. *Geografiska Annaler*, **1-2**: 1-54.



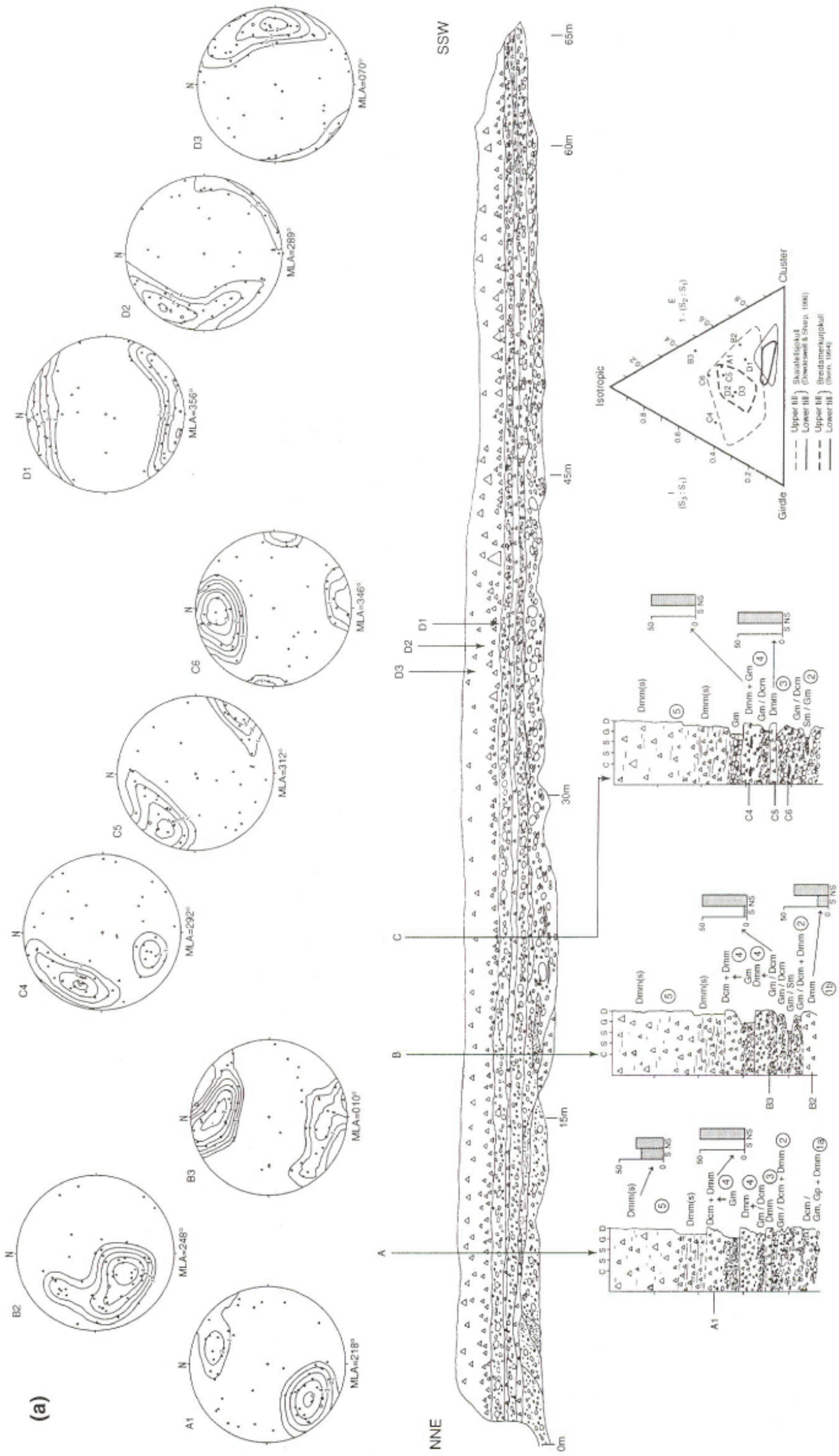
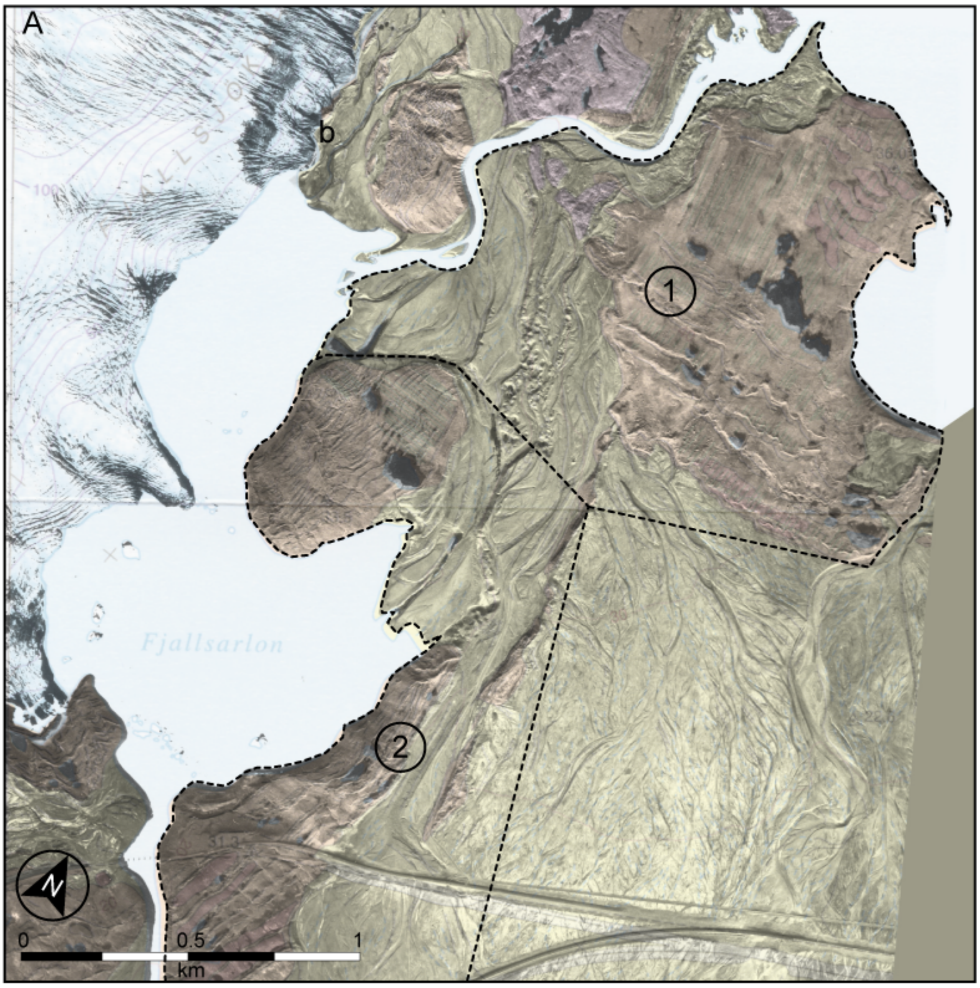
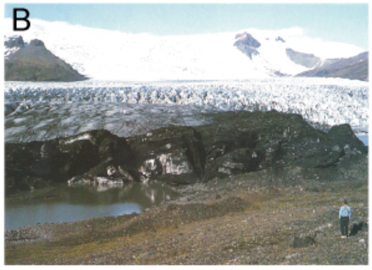


Fig. 3. (a) The Skalafellsjökull stratigraphic section (located on Fig. 2), vertical profile logs, and fabric and sedimentological data. Clast fabrics are reproduced as Schmidt equal-area projections, on which contours represent the Gaussian weighting factor. MLA = mean lineation azimuth. Vertical profile logs are coded according to the scheme in Fig. 1 and LFAs are numbered 1–5. Histograms record the number of striated (S) and non-striated (NS) clasts in the fabric samples. The fabric shape triangle plots isotropy against elongation for each fabric sample (after Benn 1994a) and includes fabric shape envelopes for previously reported tills at Breidamerkurjökull and Skalafellsjökull.

UNIT 20: MAPPING EXERCISE
Application of landsystems approach

UNIT 20: MAPPING PROJECT *Application of landsystems approach*





A. Area of mapping exercise. This figure shows an aerial photograph, taken in 1998, overlain on the University of Glasgow's Breidamerkurjökull combined glacial geology and geomorphology map (1998).

B. Example of a small push moraine at the snout of Fjallsjokull (at 'b' on map, photo D.J.A. Evans).

C. Flutings on Breidamerkursandur. Note deflection of the nearest flute around the boulder. Ice flow from right to left (photo, D.I.Benn).

D: Degraded flute at the margin of Skalafellsjökull showing the relationship to a lodged, faceted boulder. Note perched erratic on up-ice side of boulder. Ice flow away from viewer (photo D.J.A. Evans).

AIMS OF THE MAPPING EXERCISE

1. To map an area of modern glacial deposits applying the landsystem approach.

2. To describe and record the lithofacies associations encountered within a self-contained and diverse glacio-geological system.

3. To develop an understanding of the timing of glacial and glaciofluvial processes, and the rate of landscape evolution, in a contemporary ice-marginal environment.

ORGANISATION

There will be four groups of three mappers. Two groups will work Area 1 and two groups in Area 2, as shown on figure A (above). These areas have been specifically chosen as they display an excellent range of deposits and landforms, comprising several different landsystem units.

Rather than simply producing a standard BGS-style geological fieldslip, try and use all of the information and techniques covered in the fieldcourse (eg. section logging, lithofacies analysis, combined with tephrastratigraphy and lichenometric techniques, etc.) to compile a geological landscape map which could be used to reconstruct the relative timing of events.

OUTPUTS

1. An accurate, combined, geological & geomorphological map comprising:
   a) Individual landsystem units with associated lithofacies
   b) Detailed study of landsystem elements (features such as moraines, kettle holes, meltwater channels, etc.)

2. Fully described section logs from several different glacial sediment assemblages.

3. A relative chronology, based on geomorphological observations combined with information regarding tephra occurrence and/or lichen growth.

It may not be possible for everyone to achieve all of the outputs by themselves, so a degree of teamwork is required. We will have time on the evening before the mapping exercise to discuss a group strategy. Keeping in contact, by mobile phone or walkie talkie, throughout the mapping exercise will enable better understanding of the 'big picture'.

KIT REQUIRED

AIR PHOTO	HI-VIS VEST
OUTLINE MAP	GPS
PENCIL	MOBILE PHONE
RULER	WATERPROOFS
COMPASS CLINO	HAT AND GLOVES
TROWEL	
SPADE	
CAMERA	

APPENDIX 1: LITHOFACIES CODES *(according to Miall, 1978)*

Facies Code	Lithofacies	Typical sedimentary structures	Interpretation
GRAVEL, G:			
Gm	gravel, unstratified or crudely bedded, clast-supported	horizontal bedding, imbrication	Longitudinal bars, lag deposits, sieve deposits
Gt	gravel or sandy gravel, stratified	trough crossbeds, channel fills	Minor channel fills
Gp	gravel or sandy gravel, stratified	planar crossbeds	Linguoid bars or deltaic growths from older bar-remnants.
GP	gravel or sandy gravel, stratified	large-scale (>2 m) foresets	Delta foresets
Gms	massive, matrix-supported gravel or sandy gravel	none	Debris flows
Gc	gravel, clast-supported	imbrication	Insufficient data alone
Gco	gravel, clast-supported, openwork (shingle)	imbrication	Beach shingle, foresets
Gb	breccia	imbrication	Scree, Head
B	boulder gravel	imbrication	as Gm. Gms. Flood events
SAND, S:			
St	sand, medium to very coarse, may be pebbly	solitary or grouped trough crossbeds	Dunes (lower flow regime)
Sp	sand medium to very coarse, may be pebbly	solitary or grouped planar crossbeds	Linguoid transverse bars, sand-waves (lower flow regime)
SP	sand, medium to very coarse, may be pebbly	large-scale (> 2m) foresets	Delta foresets
Sr	sand, very fine to coarse	ripple marks of all types, including climbing ripples	Ripples (lower flow regime)

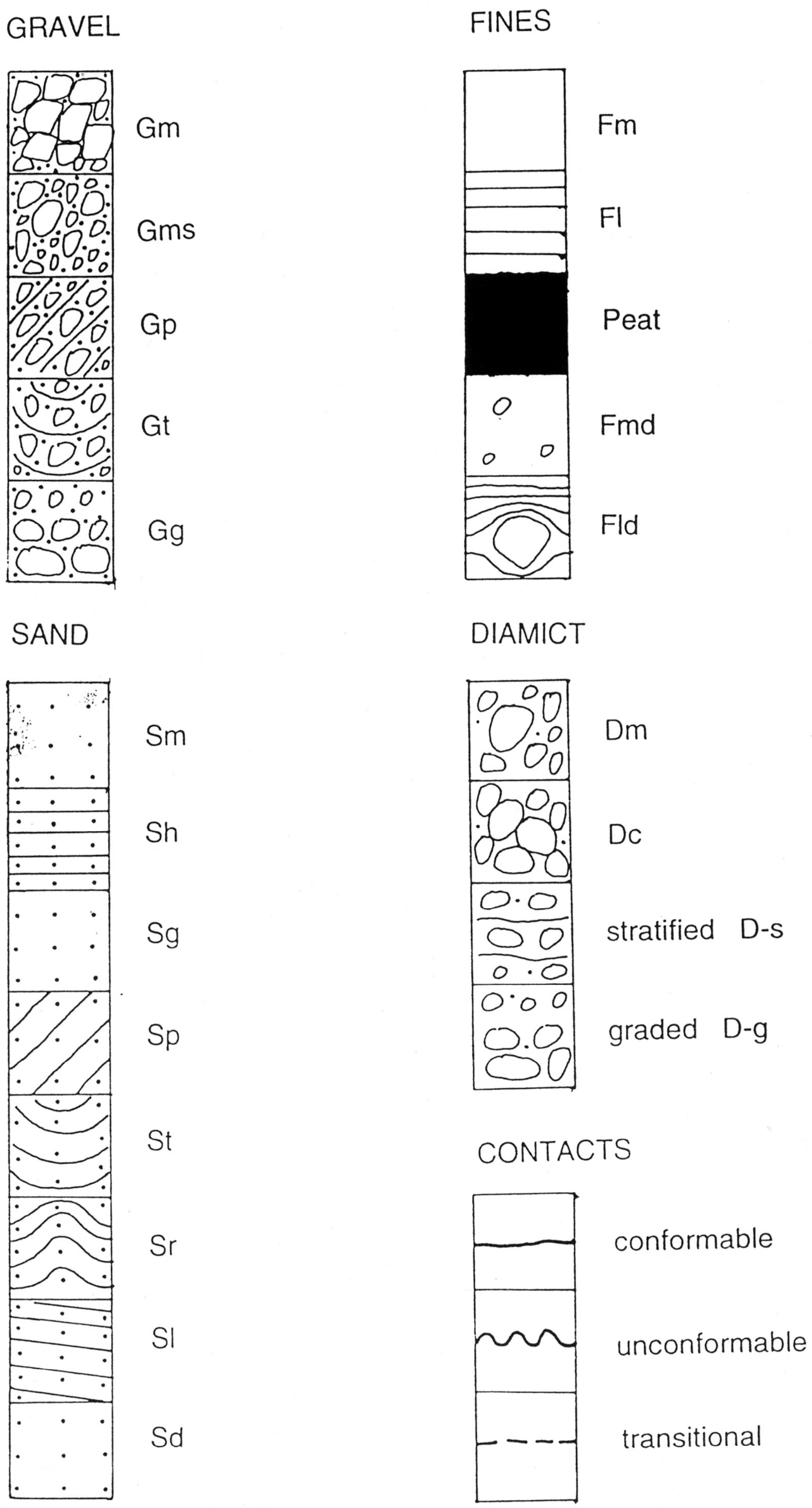
APPENDIX 1: LITHOFACIES CODES *(according to Miall, 1978)*

Sh	sand, very fine to very coarse, may be pebbly	horizontal lamination, parting or streaming lineation	Planar bed flow (lower and upper flow regimes), Aeolian deposits
Sl	sand, fine	low angle (<10°) crossbeds	Scour-fills, crevasse-splays, antidunes.
Se	sand, fine to coarse, with intraclasts	crude cross-bedding, erosional scours	Scour-fills
Ss	sand, fine to coarse, may be pebbly	broad, shallow scours including cross-stratification	Scour-fills
Sm	silty sand, massive	none	Insufficient data alone
Sd	sand, deformed	soft-sediment deformation, convolute bedding, etc	Loading, palaeoseismicity, periglacial thaw consolidation.
Spa	sand, medium to coarse	high angle, planar cross-stratification	Aeolian dunes
Sra	sand, fine to medium	adhesion ripples, broad, shallow scours	Glacio-aeolian deposits
Sc	sand, contorted	small and large scale disturbance	Cryogenic and/or glacitectonic structures, slumping
Sg	sand, graded	erosional bases common	turbidites, glacio-estuarine deposits
FINES, F:			
Fl	fine sand, silt, mud	wavy to parallel (horizontal) lamination, low-amplitude ripples	Overbank or waning flood deposits, glaciolacustrine deposits
Fh	silt, mud	parallel (horizontal) lamination	glaciolacustrine deposits, backswamp deposits
Fm	mud, silt	massive	glaciomarine deposits, backswamp deposits
Fhd	pebbly silt, mud	laminated with dropstones	glaciolacustrine deposits

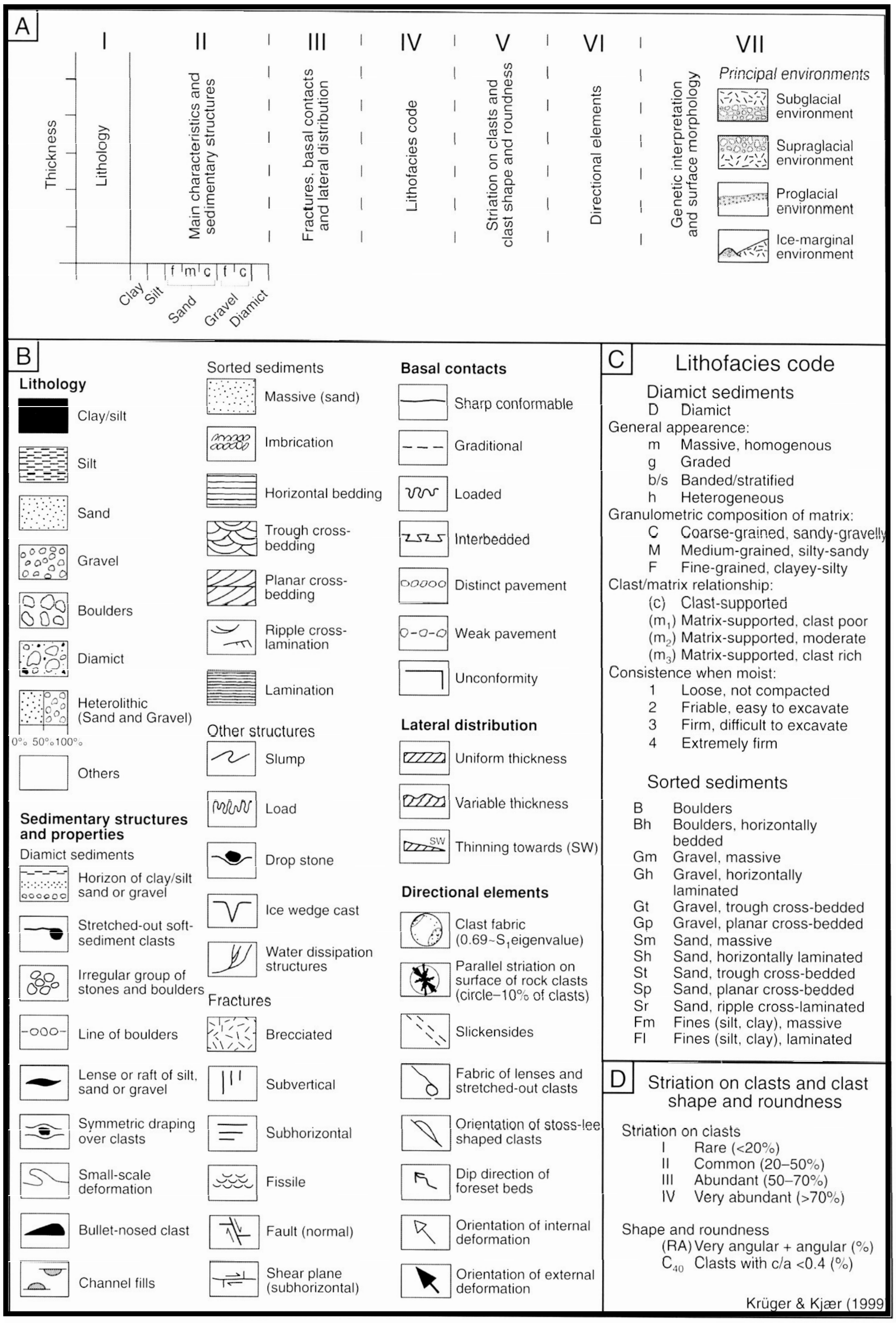
APPENDIX 1: LITHOFACIES CODES *(according to Miall, 1978)*

Fmd	pebbly mud, clay	massive, well dispersed clasts	Glaciomarine, waterlain till, debris flow
DIAMICTON D:			
Dm	diamicton, matrix-supported	none	Insufficient data alone
Dcm	diamicton, clast-supported	none	Head, Talus
Dmm	diamicton, matrix-supported, massive	structureless, very-poorly sorted mud/sand/gravel admixture, dispersed clasts, glacially bevelled and scratched clasts common	Lodgement till if grossly overconsolidated, cohesive debris flows
Dmm(c)	Dmm with evidence of current reworking	laterally discontinuous wispy laminae of fine sand/silt produced by traction currents	Meltout till. Some laminae may be result of shearing.
Dm-(r)	Dm with evidence of resedimentation	fold noses, rafts of deformed silt/clay laminae, rip-up clasts	Flow till, cohesive debris flows.
Dms	Diamicton, matrix-supported, stratified	stratification is pronounced and more than 10% of unit thickness, often graded, generally laterally discontinuous stacked beds, pronounced winnowing, lenses of water-sorted, stratified sand and gravel	Flow till, meltout till
Dmg	Diamicton, matrix-supported, graded	clast content generally graded	Cohesionless debris flows, turbidites

APPENDIX 1: LITHOFACIES CODES *(according to Miall, 1978)*

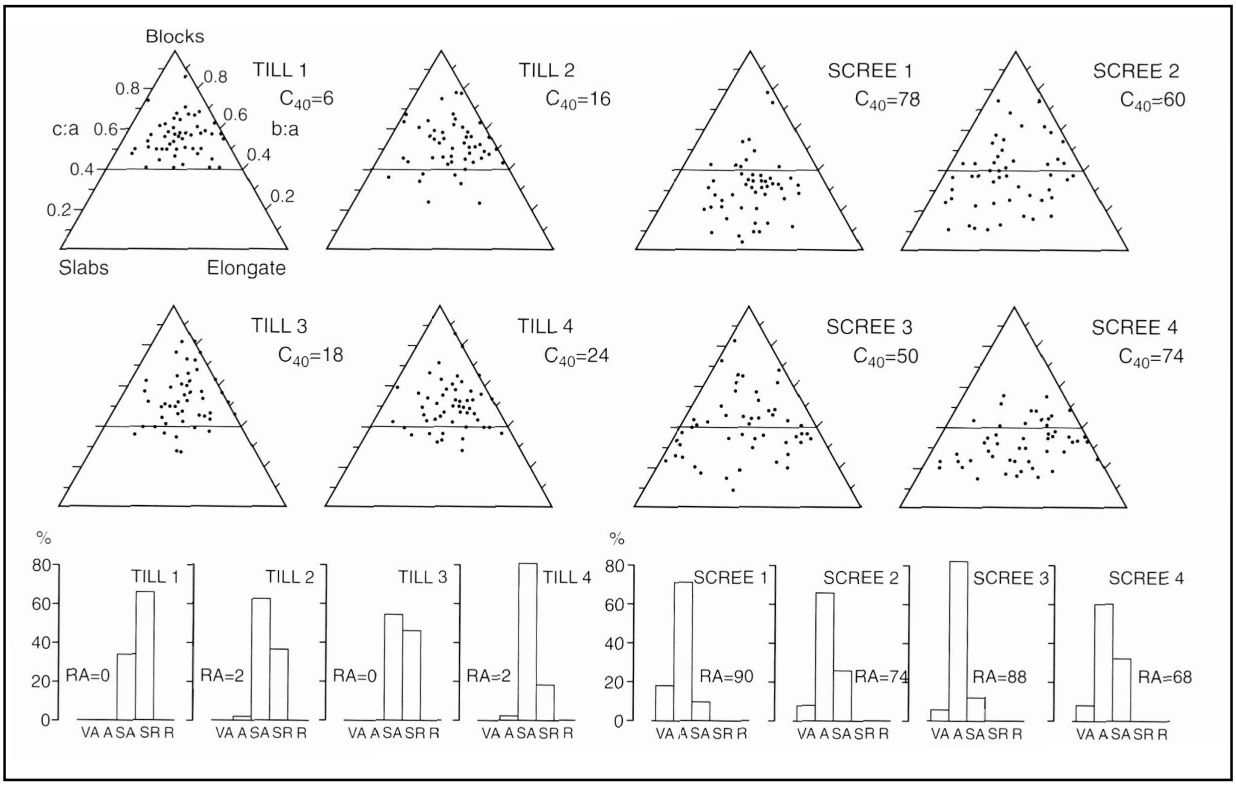


APPENDIX 2: DATA CHART FOR FIELD OBSERVATIONS *(Kruger & Kjaer, 2000)*

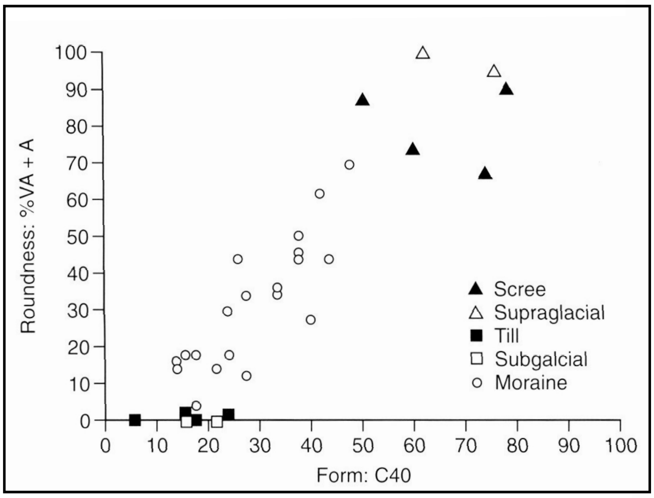


Data chart for recording field observations (Kruger & Kjaer, 2000). A: Structure of data chart, showing information to be entered in each column; B: Symbols for recording lithological and structural data; C: Lithofacies codes; D: Definition of terms used to summarise clast form data.

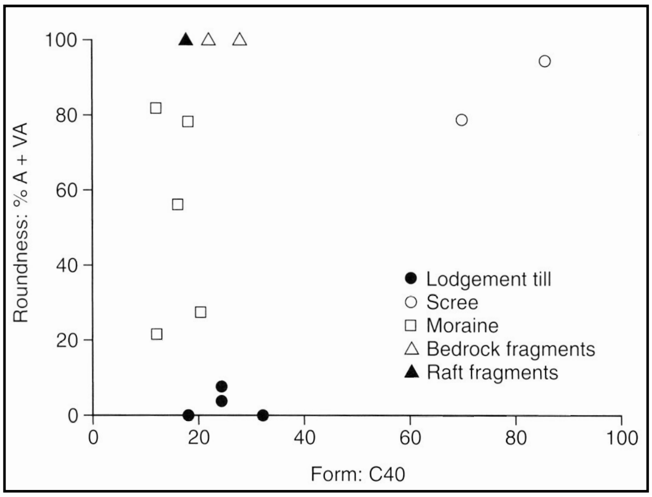
APPENDIX 3: CLAST MORPHOLOGY AND CO-VARIANCE ANALYSIS



Clast-shape and roundness data for subglacially-deposited debris (basal till) and rockfall debris (scree), near the margins of Storbreen Norwegian corrie glacier. (From Ballantyne & Benn, 1994)



RA-C40 diagram showing clast-shape and roundness data from Storbreen. Control samples are from scree, passively transported supraglacial debris, basal till and debris from basal debris-rich ice. The moraine samples plot a s a band between the two sets of control samples, suggesting that they comprise mixtures of debris from passive and active transport paths. (From Benn, 2004).



RA-C40 diagram for data from Glen Arroch, Skye. Control samples are from scree, basal till and fragments prised from roadside bedrock exposures and rock rafts contained in the moraines. Clast samples from the moraines plot as a vertical band between the rock fragment controls and the basal till controls, suggesting that they consist of rock fragments quarried from the glacier bed, which have undergone varying amounts of edge rounding but little or no change in shape. (From Benn, 1992).