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Responses of mountain ice caps in central Iceland to Holocene climate change

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Abstract

A chronology of Holocene fluctuations of small outlet glaciers from the Regnabuðajökull ice cap on Hrútfell, central Iceland, allows comparison of their sensitivity with the margin of the nearby Langjökull icefield, to ascertain which frequencies of climatic variability are recorded by adjacent glaciers of different size. Dating utilised tephra layers in aeolian soils lying on, between and beneath moraine ridges. Key marker isochrones dating from the Hekla 4 tephra (*c.* 3.8 ka BP) to Katla A.D. 1918 provide unequivocal bracketing ages. The stratigraphy and geochemical fingerprinting of tephras on younger moraines allows subdivision of "Little Ice Age" moraines. Five groups of moraines are identified, at *c.* 4.5–5.0, *c.* 3.0–3.5 ka BP, *c.* 2.0–2.5 ka BP, and from the "Little Ice Age" at *c.* A.D. 1700 and in the late 19th/early 20th century. These represent a Neoglacial sequence in which steep, small glaciers readvanced to similar positions during what are here termed "Little Ice Age"-type periods (LIATPs). In contrast, the nearby margins of Langjökull show evidence of a late nineteenth-century advance only, suggesting that this was the Holocene maximum for this glacier. The contrasting responses of local glaciers and the large icefield are explained by their different sizes and response times, so that the preserved moraine record is largely pre-conditioned by the glacier type. In general, the forefields of steep, fast-responding glaciers contain more complete archives of Holocene climatic changes than do the margins of the large icefields.

1. Introduction

This paper presents the results of morphostratigraphic investigations at the forelands of four small glaciers in west-central Iceland, and contrasts these results with the findings from the nearby margins of the large Langjökull icecap (Fig. 1). The aims are twofold: first, to establish a reliably dated Holocene chronology for the local glaciers to aid correlations between northern and southern Iceland: and second, to establish whether different marginal responses to Holocene climate variations are a result of dynamic contrasts between large and small glaciers (Björnsson, 1979; Jóhannesson, 1986), or due to the greater preservation potential of ice-marginal landsystems at small glaciers compared to larger ones (Kirkbride and Dugmore, 2001a). The study site was chosen because of the concentration of, and therefore climatic similarity between, the two main glacier types in Iceland. All five study glaciers have well-preserved and dateable moraine sequences.

The Holocene glacial chronology for Iceland is marked by apparent regional variation, which may reflect either regional emphases on different dating techniques, or real contrasts in glacial history. Generally, it appears to be dominated by late "Little Ice Age" (LIA) advances, especially in the south, to the extent that the maxima in the late 19th and early 20th centuries are taken by some authors to represent the Holocene glacial maximum (Caseldine and Stötter, 1993; Evans et al., 1999), in spite of evidence to the contrary (e.g. Stötter, 1991, 1994; Guðmundsson, 1997; Stötter et al., 1999; Kirkbride and Dugmore, 2001a). Earlier events are poorly known, and are mainly based on radiocarbon and tephrochronological dating of the moraines of cirque glaciers in Tröllaskagi in the north (Wastl et al., 2001). Apparent differences in LIA chronology across Iceland have led some authors to suggest regional climatic differences as the cause (e.g. Guðmundsson, 1997). Evidence of pre-LIA moraines in

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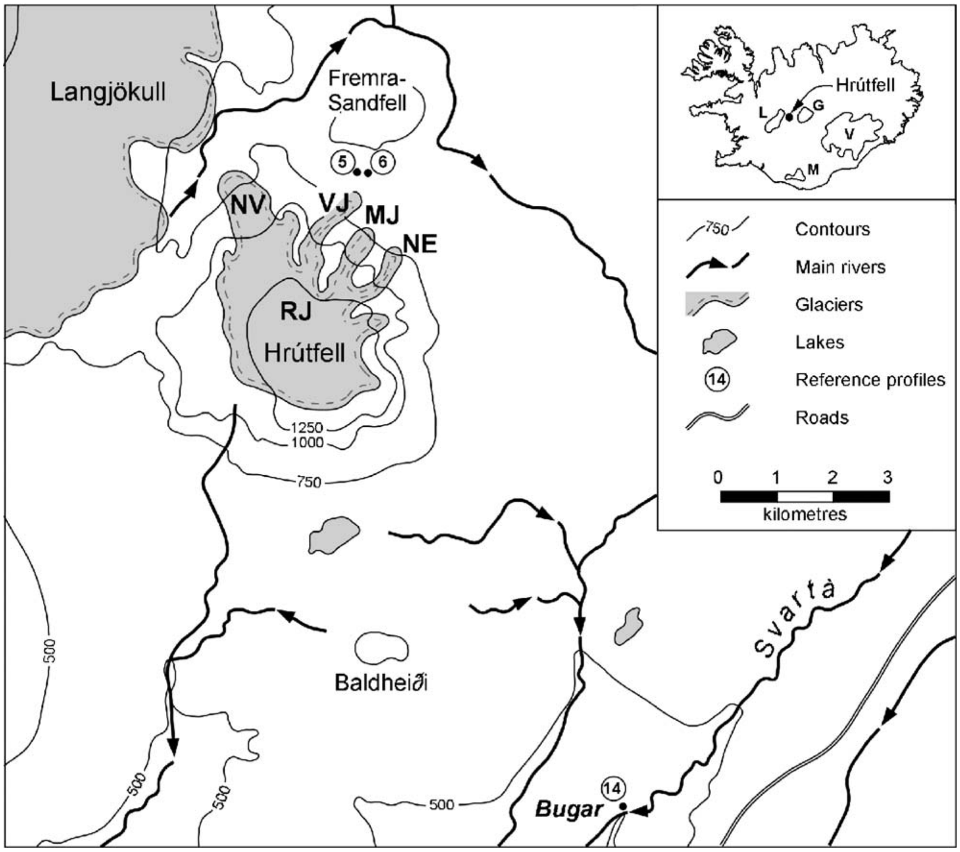

Fig. 1. Location map of Hrútfell and the outlet glaciers of Regnabuðajökull. RJ = Regnabuðajökull; NV = Norðvesturjökull; VJ = Vesturjökull; MJ = Miðjökull; NE = Norðurkinn-Eystri. Inset: the main ice caps are L = Langjökull, G = Hofsjökull; V = Vatnajökull; M = Mýrdalsjökull. Circled numbers mark the locations of reference soil profiles presented in Fig. 5.

various parts of the country (Guðmundsson, 1997; Kirkbride and Dugmore, 2001b; Schomacker et al., 2003), together with new data on changes in oceanography of the shelf bordering the north-western coasts (Eiríksson et al., 2000; Andrews et al., 2001, 2003) open up new possibilities for improving chronologies and correlations between various palaeoclimatic proxies.

For these reasons, we report here on an unusually complete dated moraine sequence from a location in interior Iceland, which helps to link the local glacial chronologies from northern and southern Iceland (cf. Stötter et al., 1999; Kirkbride and Dugmore, submitted).

2. Regnabuðajökull and its outlet glaciers

Hrútfell (Fig. 1, 64°45′N 19°45′W) formed by subglacial volcanism during the Pleistocene, giving the characteristic *stapi* form of a steep-sided plateau of hyaloclastite and pillow lava (Guðmundsson, 1996). Though its summit at 1396 m is higher than Langjökull to the west, the rain-shadow effect of the much larger ice cap means that precipitation reduces from *c.* 4000 mm a^{-1} over the northern dome of Langjökull to *c.* 2000 mm a^{-1} over Hrútfell. Mean annual temperature is probably slightly below 0 °C (1936–1985 average from data collected by Vedurstofa Islands). The Regnabuðajökull ice cap mantles the plateau of Hrútfell, and four steep outlet glaciers descend from it: Norðvesturjökull to the north-north west, and Vesturjökull, Miðjökull and Norðurkinn-Eystri to the north-east (see Appendix A on place names). These latter three glaciers formerly coalesced as a piedmont lobe, but are no longer contiguous. All terminate close to 700 m above sea level. At each glacier, moraines are labelled according to glacier name and numbered in the proximal-to-distal direction.

2.1. Norðvesturjökull (Fig. 2)

Two terminal moraines, NV1 and NV2, form arcs around the foreland. Between NV1 and the present glacier lies a broad arcuate ridge mantled by fluted till, possibly an overridden terminal moraine (NVX). This moraine is older than NV1 and may also be older than NV2. Outside NV1 lies a vegetated moraine ridge NV2 which fronts onto the floodplain. To the west lies a lateral fragment NV3. The present outwash stream has incised into the former outwash surface to reveal a section through NV2 and the underlying sediments (described below).

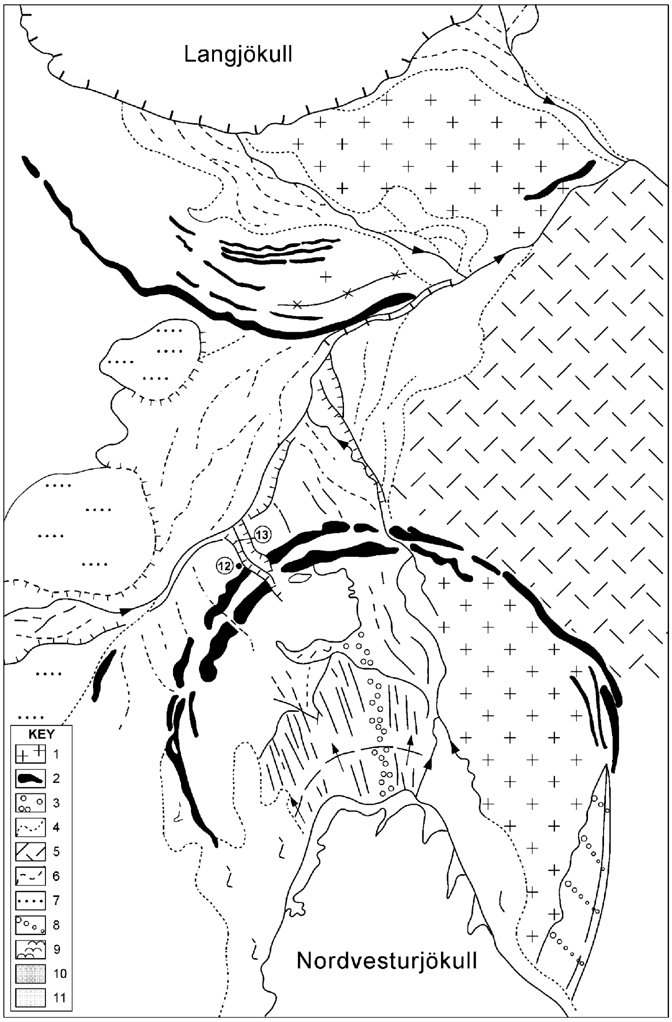

Fig. 2. Geomorphological map of Norðvesturjökull, showing the location of soil profiles (circled numbers) relative to moraine ridges described in the text. Key to symbols for Figs. 2 and 3: 1 = outwash alluvium; 2 = moraine ridges; 3 = medial moraine (dispersed boulders); 4 = ephemeral outwash channels; 5 = heath; 6 = palaeochannels; 7 = terrace surfaces; 8 = large lateral moraines; 9 = deformed ice-cored moraine; 10 = supraglacial debris; 11 = unvegetated foreland. Arrows through dashed lines indicate overridden moraines.

2.2. Vesturjökull (Fig. 3)

The youngest group of moraines (collectively VJ1) includes an overridden lateral moraine ridge on western glacier margin (VJX) and a former ice-cored rock glacier lobe derived from debris-covered marginal ice (Fig. 3). Distal to these deposits, but overridden by them in the west, lie segments of a vegetated arc VJ2 (Fig. 4). At the time of formation of this moraine, the glacier would have crossed the present river and run up against the steep 20 m-high north bank, above which lie moraines VJ5 and VJ6. Lateral moraine segments VJ3 and VJ4 flank the north-western margin of the foreland. VJ4 is morphologically similar to VJ2, bearing a cryoturbated soil and tephra cover. The degraded VJ3 lies in between, but could not be dated due to disturbed soil cover. VJ5 and VJ6 are located north of the river, and east and west of a rock gorge. Both moraines have caused tephra-bearing dunes of aeolian silt to accumulate along their distal slopes. Their preservation has been favoured by the higher level of the northern river bank which was reached only by older, more extensive glacier advances.

2.3. Miðjökull and Norðurkinn-Eystri (Fig. 3)

The contiguity of moraines of similar morphology and configuration in these two glacier forelands allows them to be described together. Moraines fall into two groups. The older group comprises contiguous vegetated ridges MJ2 and NE2, which are the south-eastward continuation of the VJ2 moraine. These lie outside younger groups of multiple unvegetated moraines whose distal bounding arc is MJ1-NE1 (Fig. 4). Representatives of the older groups of moraines found at Vesturjökull are not preserved at Miðjökull and Norðurkinn-Eystri due to aggradation in the proglacial area.

2.4. Moraines of the outlet lobes of Langjökull

Three termini from the Langjökull ice cap descend to the floodplain of Sanddalur. The southern terminus was visited, whereas the central and northern termini were inaccessible. No tephra layers were found within the terminal moraine of the southern lobe. At all three termini, only a single unvegetated "fresh" moraine ridge exists. At the northernmost of these lobes, the foreland is distant from Holocene floodplains and from steep slopes and is favourable for the preservation of older glacial deposits, yet none are found.

3. Regional tephrostratigraphy

The fundamental tephrochronology of the area has been established by Thórarinsson, Larsen and others (Thórarinsson, 1966, 1967, 1975; Larsen and Thórarinsson, 1977; Larsen, 1981, 1984; Larsen et al., 1999, 2001). The key marker horizons are formed by four major silicic tephras produced by Hekla. Two distinct historic-age tephras are Hekla 1 (H1104) and the Landnam tephra. The latter was produced by simultaneous eruptions in the Veidivotn (Vatnaodalur) volcanic system and the Torfajökull central volcano (Larsen, 1984) and dated to 871 ± 2 in the GRIP ice core (Grönvold et al., 1995). Hekla-3 (H3) was ^{14}C dated to 2850–3210 cal yr BP (2σ) by Dugmore et al. (1995a), an age range which later work confirms (van den Bogaard et al., 2002). Hekla-4 (H4) has been dated by ^{14}C to 3834 ± 15 yr BP, or 4080–4420 cal yr BP (Dugmore et al., 1995a) and 4150–4360 cal BC (Pilcher et al., 1995). These and other age estimations are summarised by Zillén et al. (2002). The age of Hekla 5 (H5) is less well constrained to *c.* 6200 yr BP by Larsen and Thórarinsson (1977). Key subdivisions of recent centuries, essential for constraining LIA events are achieved by identifying fallout from the

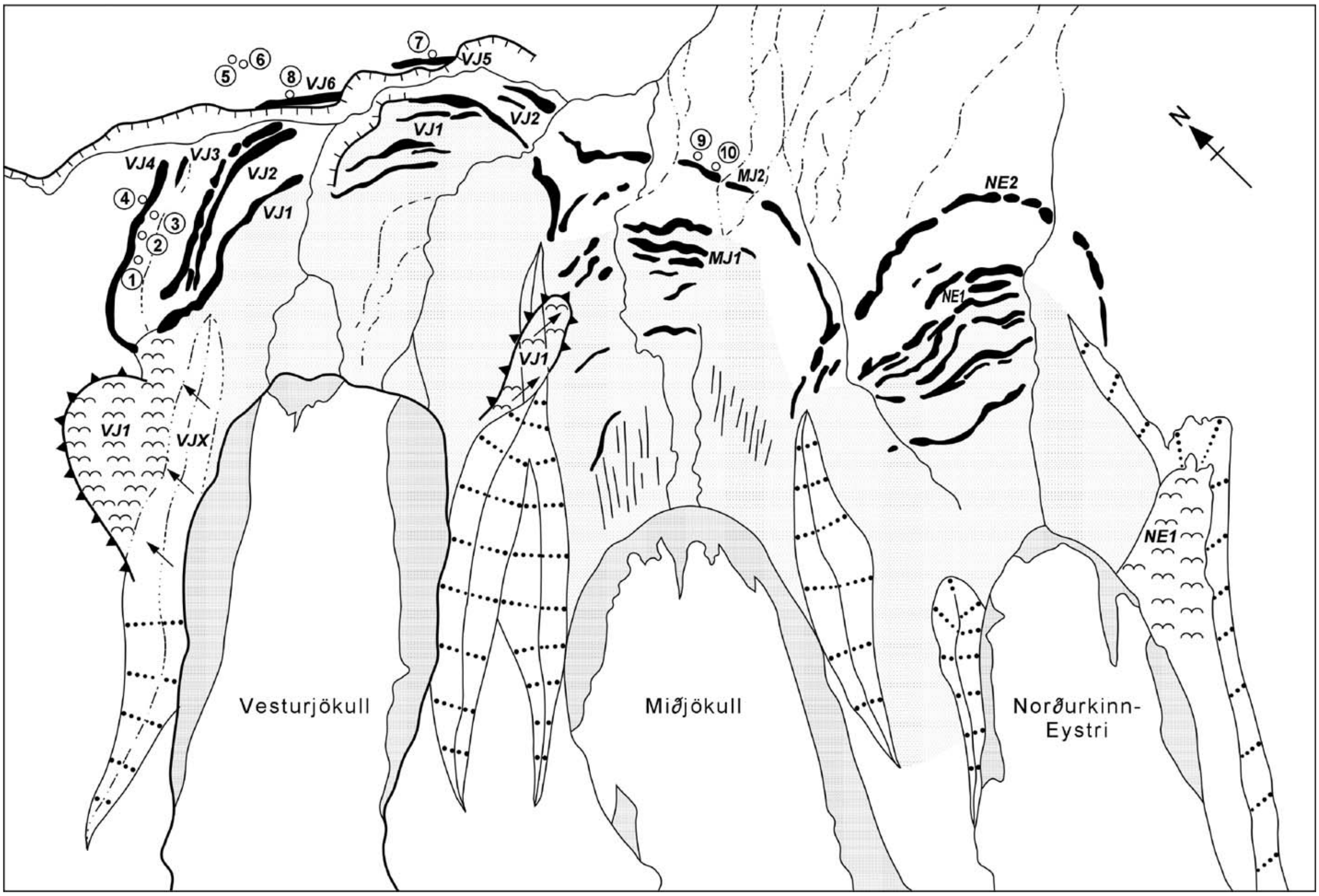

Fig. 3. Geomorphological map of the glaciers Norðurkinn-Eystri, Miðjökull, and Vesturjökull. Circled numbers mark the locations of soil profiles: a selection of key profiles is presented in Figs. 5 and 7. See Fig. 2 for key to symbols.

Fig. 4. The forelands of Norðurkinn-Eystri (NE, left), Miðjökull (MJ), and Vesturjökull (VJ, right), showing the field relations between the moraines of Group 1 and Group 2.

Katla eruption of 1721 (Thórarinsson, 1975) and the Hekla eruption of 1766 (Thórarinsson, 1967).

Reference profiles were logged in soil sections excavated beyond the influence of Holocene glaciers (Fig. 1). These include one pit close to the distal moraine of Vesturjökull (Profiles 5 and 6), and another in deep soils at the Bugar Ford, several kilometres to the south-east (Profile 14) (Fig. 5). The Hrútfell stratigraphy can be correlated with the sequence to the south and south-west. The pattern revealed is one of thinning soil cover and more distal fallout north of the Hekla volcano, dominated by the major silicic tephras H1104, V870, H3 and H4. Some marker layers which occur at Hagafellsjökull-Eystri are absent at Hrútfell. One such layer is the H1693 tephra, which peters out just to the south and west of the study site. Though the number of useful isochrones is fewer to the north, the presence of the major markers and several other dated layers provides a workable and robust temporal framework in which to investigate moraine ages.

Detailed field mapping of stratigraphy is the first step in the use of tephrochronology. Within soil and other sediment sequences tephras are identified by their glass composition, particle size, shape and vesicularity, layer thickness, layer colour, sedimentary structures within the layer, and distinctive non-glass components of tephra layers such as mineral fractions and grains of scoria. The degree of disturbance of the soil cover by cryoturbation at the altitude of the study site is greater than that at sites close to sea level in the south (Dugmore, 1989; Kirkbride

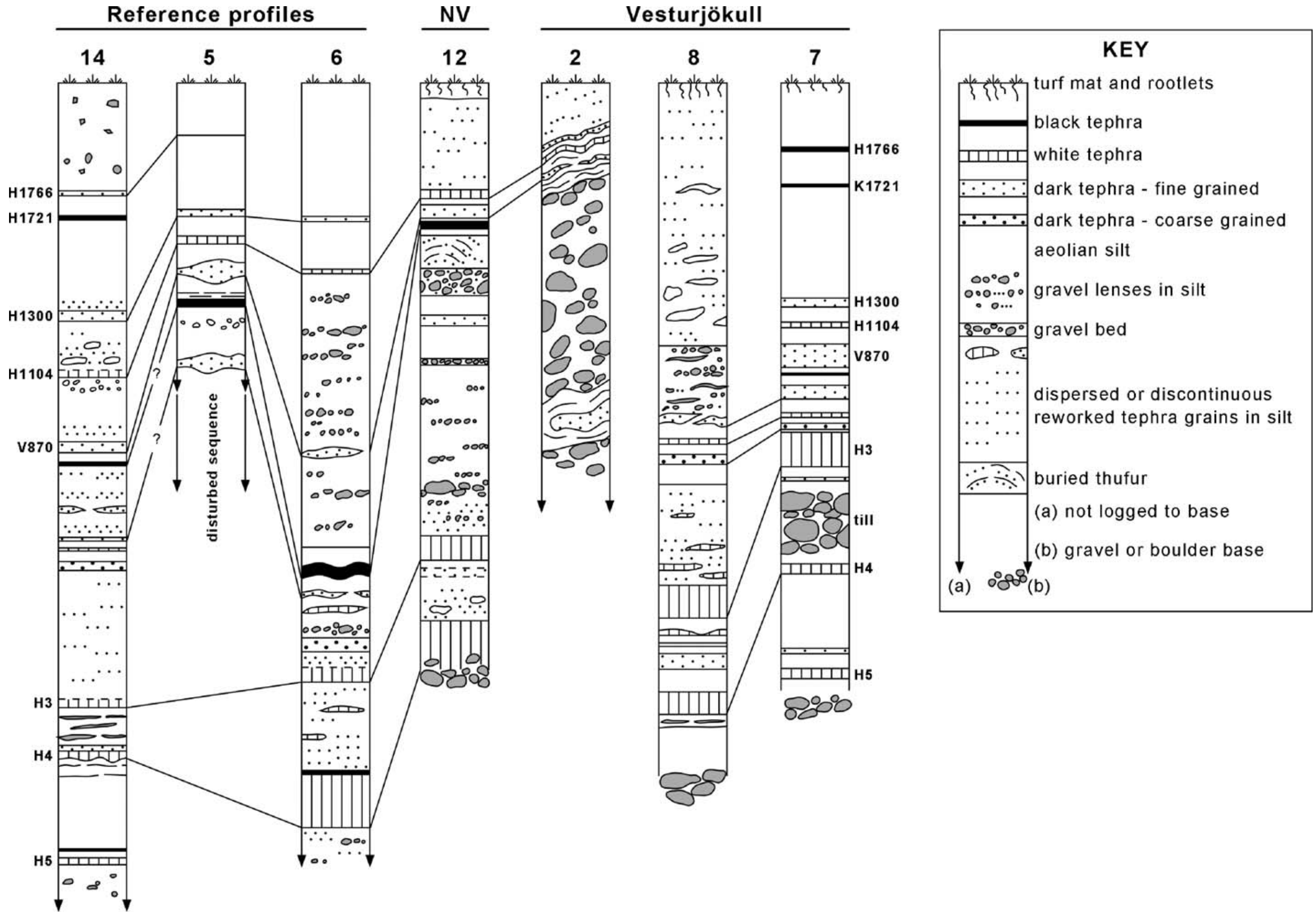

Fig. 5. Stratigraphy of the important soil profiles excavated at Hrútfell. Profiles 5, 6 and 14 are reference profiles located away from the influence of Holocene glaciers (see Fig. 1 for locations). Profiles 2, 7, 8, and 12 are truncated profiles developed upon glacial tills and are discussed in detail in the text.

and Dugmore, 2001a). This is manifest at different locations by cm-scale involutions affecting some layers, metre-scale overturning giving repeated, inverted sequences, and diffusion of tephra grains up into overlying aeolian silts. At all the profiles described, a reliable stratigraphy could be constructed because the character and relative superposition of individual tephras could be ascertained. Compared to lowland locations in south Iceland, more care was needed in selecting and interpreting profiles, and a greater proportion of excavations failed to provide unequivocal basal isochrones. This meant that little reliance could be placed on a single soil pit in a moraine. In all cases, several pits were dug, or large trenches excavated across the distal moraine slope, to adequately sample the basal layers, and only the most useful profiles were logged and are presented here.

3.1. *EPMA fingerprinting of tephra layers*

Samples of tephra layers used as regional isochrones were sampled for electron probe microanalysis (EPMA) in order to confirm their field identification. This was particularly necessary in sediments whose stratigraphy had been disturbed by periglacial activity (for example the soil cover on moraine VJ4) or truncated by later fluvial action. Also analysed were tephras of unknown provenance and age, whose identification would help to partition particular periods of time. In particular, the dark tephras in shallow soils have the potential for subdivision of LIA advances.

The samples were analysed with a Cameca SX100 electron microprobe using a standard WDS (wavelength dispersive) technique, an accelerating voltage of 20 kV and a regulated beam current of 4 or 10 nA, and a rastered beam diameter of about 5 μm. Ten major elements were analysed using five spectrometers and a peak counting time of 10 s for each element. Standards of known composition, comprising a mixture of pure metals and simple silica compounds were used for calibration. Counter dead time, fluorescence and atomic number effects are corrected using a PAP correction programme. At regular periods throughout all analytical sessions, an andradite of known composition was analysed, in order to guard against unexpected variation in machine operating conditions.

TiO_2/FeO plots of silicic (white) tephras reveal two dominant clusters (Fig. 6a). One corresponds to the known

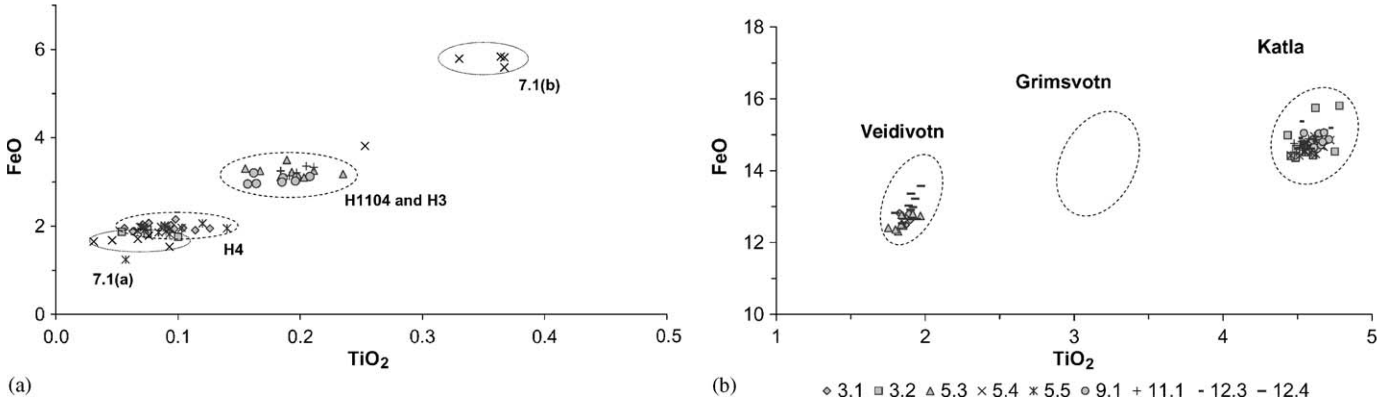

Fig. 6. Geochemistry of (a) siliceous and (b) basaltic tephra layers from glacier forelands and reference profiles. Sample numbers in (a) and below (b) are given as profile/sample (e.g. “7.1” refers to sample 1 from soil profile 7), and are referred to in the text. The heavy dashed lines mark the known compositional fields of particular tephras, while symbols mark individual original analyses.

compositional field of H4, the other to the field of H3 and H1104. The latter are chemically identical, and are distinguished on the basis of their stratigraphic relationships (Fig. 5). EPMA confirms the field identification of all silicic layers except for sample 2.1, which was initially recorded in a disturbed sequence on moraine VJ4 as putative H1104, but is instead shown to be H4. This highlights the value of the dual approach to tephrochronology of field stratigraphy backed up by EPMA. Sample 7.1 is a white tephra stratigraphically below H4 in the soil cover on moraine VJ5 and was putatively logged as H5. Analyses of 10 glass grains show two clusters: four analyses (7.1(a)) have higher TiO_2 and FeO than H3, while five analyses plot marginally but distinctly lower in TiO_2 than H4. The tephra is compositionally distinct from H3, H4, and from the Lairg “A” and “B” tephras of similar age in Scotland (Dugmore et al., 1995b). The clusters are probably spurious, as the spread of points falls within the full compositional range of Hekla’s silicic tephra.

TiO_2/FeO plots of basaltic (black) tephras also shows two clusters (Fig. 6b). The low-TiO_2 low-FeO cluster corresponds to the known compositional field of tephra from the Veidovotn volcanic system (Larsen et al., 1999). The high-TiO_2 high-FeO cluster corresponds to tephra from the Katla volcano (Boygle, 1994). Tephra layers from individual eruptions within these clusters are geochemically indistinguishable, but unique sequences of Katla and Veidivotn tephras intercalated with known silicic layers within the historic period provides useful stratigraphic information because the dates of many eruptions are known (e.g. V870, K1721, H1766, K1918). No tephra from Grimsvotn (Larsen et al., 1998) occurs in the field area.

Black layers from shallow soils on moraines of VJ2, MJ2 and NE2 could not be identified by their macroscopic features, yet potentially allow finer dating within the LIA. A sample from each of two tephras (10.1 and 10.2) was analysed by EPMA and results are discussed below.

4. Dating of glacier advance stages

4.1. Group 1—Moraines of the late “Little Ice Age”

Group 1 comprises moraines NV1, VJ1, MJ1, and NE1. Dating in the field was not possible due to the lack of tephras in the thin and patchy soil cover (Fig. 4), and few *Rhizocarpon* thalli on decimetre-sized till boulders. The earliest topographic map of the area was published in 1945 based on aerial photographs taken in 1937 and 1938. The glaciers in the late 1930s appear to have had slightly smaller extents than those delimited by the Group 1 moraines. Many glaciers in Iceland began to retreat rapidly in the 1930s (Jóhannesson and Sigurðsson, 1998; Sigurðsson, 1998; Kirkbride, 2002), having maintained fairly constant volumes since the beginning of the 20th century. On this basis, the Group 1 moraines at Hrútfell are assigned to the late 19th to early 20th century. The single moraines at the three termini of Langjökull are grouped with the youngest Hrútfell moraines. Soil profiles among the Group 1 moraines lack the thin dark tephras found at shallow depths in soil profiles elsewhere (Fig. 5). The youngest such tephra is the K1918 layer, its absence being consistent with an early 20th-century date for the Group 1 moraines.

4.2. Group 2—moraines of the LIA maximum of the 17th–18th centuries

The contiguous moraine arcs VJ2–MJ2–NE2 form Group 2. Dating of these moraines depends on the identification of three thin dark tephra layers which occurred in the aeolian soils on the distal slopes of the moraine ridges. Twenty-nine shallow pits were excavated to reveal the tephra sequence in the soil cover on the Group 2 moraines. The three tephras occurred together in only five pits at Norðurkinn-Eystri (Fig. 7, profiles 22, 26–29). The complete sequence consisted of two fine-grained jet-black tephras separated by a coarse-grained dark tephra containing grains of red scoria. The lower black tephra therefore provides the minimum age of the moraine. Where it was found, this tephra filled the interstices between till cobbles on the moraine slope and did not drape over protruding till clasts. The airfall therefore occurred shortly after the glacier retreated from the moraine. This tephra was found below the coarse scoria-bearing tephra in four out of 17 pits in the Miðjökull moraine (Fig. 7, profiles 10, 17, 18 and 20), and was not found in four pits in the Vesturjökull moraine. This patchy occurrence may reflect small differences in the timing of retreat of these glaciers from their terminal moraines rather than different advances.

EPMA of the lower jet-black tephra in profile 10 (sample 10.1) and coarse scoria-rich tephra (sample 10.2) are presented in Table 1(a). Composition of the lower jet-black tephra corresponds to the characteristic major elements for eruptives from Katla, 130 km to the SSE (Table 1(b)). The individual eruptions cannot be unambiguously identified because the many historic eruptions of Katla have produced tephra of the identical basaltic composition. In recent centuries, Katla tephras have been blown to the north only in the eruptions of A.D. 1918 and A.D. 1721. The lower jet-black tephra mantling the Group 2 moraines is identified as K1721 by its stratigraphic position closely below the H1766 tephra (see below). The upper jet-black tephra must therefore be the Katla A.D. 1918 tephra because of the absence of other candidates in west-central Iceland in the post-AD 1766 period.

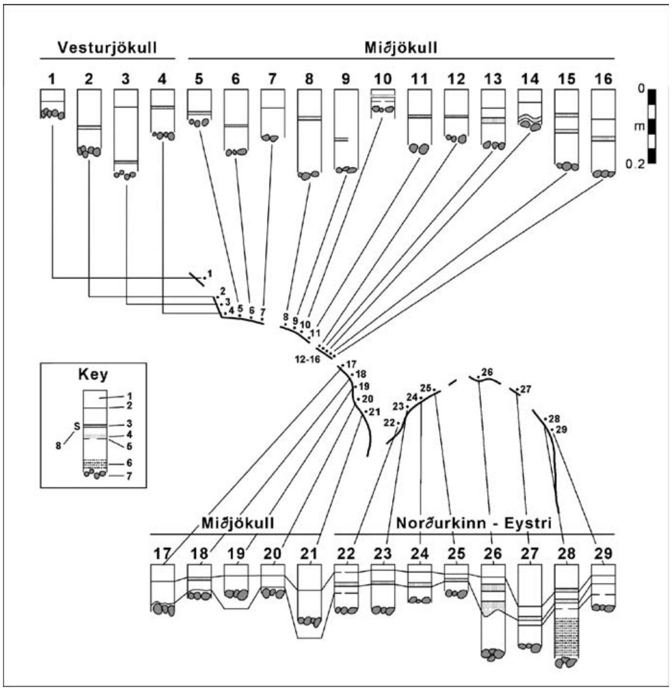

Fig. 7. Tephrostratigraphy of soil profiles excavated in the forelands of Norðurkinn-Eystri, Miðjökull, and Vesturjökull. Key to symbols: 1 = orange to brown aeolian silt; 2 = upper fine black tephra; 3 = coarse dark tephra; 4 = fine gravel; 5 = lower fine black tephra; 6 = washed sand; 7 = basal till clasts; S = sampled layers (Profiles 10 and 13). NB. The numbering of profiles at this site is independent of the regional numbering used elsewhere.

Table 1

(a) Geochemistry of tephras from the Group 2 moraines determined by electron microprobe analysis. Tephra grains were analysed on the University of Edinburgh Cambridge Instruments Microscan V using the protocols described by Larsen et al. (1999, 2001).

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	NaO	K_2O	Total
10.1/5	46.45	4.70	12.35	14.56	0.27	4.99	9.47	3.12	0.77	96.68
10.1/3	46.42	4.71	12.13	14.23	0.24	4.95	9.30	3.11	0.77	95.95
10.1/2	46.31	4.62	12.23	14.65	0.22	4.92	9.47	3.23	0.73	96.39
10.1/4	46.07	4.73	12.35	14.48	0.20	5.05	9.67	3.10	0.76	96.41
10.1/6	46.10	4.76	12.18	14.42	0.24	4.93	9.31	3.14	0.75	95.81
10.1/7	46.43	4.70	12.21	14.10	0.21	4.95	9.39	3.12	0.74	96.77
Means	46.30	4.70	12.24	14.41	0.23	4.97	9.44	3.14	0.75	96.34
10.2/6	60.25	1.16	14.90	8.67	0.20	1.72	4.96	4.35	1.82	98.03
10.2/3	59.73	1.26	15.10	9.17	0.21	1.65	5.35	3.94	1.53	97.94
10.2/2	59.72	1.16	15.18	8.88	0.26	1.97	5.68	4.33	1.39	98.58
10.2/4	59.29	1.06	14.90	8.75	0.21	1.60	4.87	4.12	1.67	96.46
10.2/7	59.27	1.20	14.90	9.02	0.27	1.57	5.10	4.01	1.64	96.98
10.2/8	59.14	1.06	14.84	9.19	0.21	1.63	5.00	3.97	1.53	96.58
10.2/5	58.54	1.09	14.75	9.21	0.27	1.59	4.83	3.98	1.63	95.90
Means	59.42	1.14	14.94	8.98	0.23	1.68	5.11	4.10	1.60	97.21

(b) Geochemistry of known "Little Ice Age" tephras found to close to the study area (data taken from the Tephrabase data archive at www.geo.ed.ac.uk/tephrabase)

Tephra	n	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	NaO	K_2O	Total
Katla A.D.1625	7	46.28	4.56	12.62	14.75	0.23	4.89	9.97	2.72	0.71	96.72
Katla A.D.1755	6	46.21	4.71	12.43	14.45	0.24	4.97	9.85	3.06	0.73	96.65
Hekla A.D.1693	13	55.23	1.64	15.31	10.96	0.40	2.59	5.66	2.97	2.19	96.95
Hekla A.D.1766	11	57.73	1.40	14.87	9.67	0.27	2.05	5.41	4.37	1.46	97.41

The composition of the coarse scoria-rich tephra found between the two Katla tephras identifies its source as Hekla, 85 km to the south (sample 10.2). Macroscopic characteristics and the dacitic composition revealed by EPMA suggest a match with either the A.D. 1693 or 1766 tephras (Table 1(b)), both of which were deposited north of Hekla. A SiO_2 content of 59–60% identifies the tephra as H1766, because H1693 has a slightly but significantly lower SiO_2 content of 58% (Thórarinsson, 1967) Stratigraphically, this date is consistent with the ages given above to the super- (A.D. 1918) and subjacent (A.D. 1721) Katla tephras.

Identification of the provenance of the tephras allows the minimum ages of the Group 2 moraines to be determined. VJ2 is older than A.D. 1766, while MJ2 and NE2 closely predate A.D. 1721. The contiguity of the moraine ridges means that all are ascribed to the same glacier advance, and changes in tephra distribution along the composite moraine arc may reflect a later retreat of glaciers to the west.

4.3. Group 3—moraines of the "Subatlantic" period

At Norðvesturjökull, the riverbank section of Profile 13 (Fig. 2) provides tephrochonological constraints on the ages of the NV2 moraine and an older buried till. The present outwash stream has incised into the former outwash surface to reveal a complex sequence of sediments which record alternations between periods of glacier advance from the upland and of non-glacial valley floor environments (Fig. 8). Five units are recognised in the section on the left bank of the river (Table 2), including two tills.

Unit 1 is poorly exposed along the base of both river banks close to the active channel. Laminated silts are interpreted as deposition in a shallow lacustrine environment, with lenses of gravel indicating fluvial channel fills, suggesting low-lying floodplain conditions with no glaciers in the immediate proximity. The till forming unit 2A contains rip-up clasts of unit 1, and lies over a sharp erosional unconformity which truncates the lamination of the lacustrine silts, and is evidence of an advance of Norðvesturjökull across the floodplain. Unit 2B represents the fluvially reworked surface of the till sheet, possibly the aggradation of a proglacial fan, after the glacier had retreated. The till of unit 2A is traceable as a buried layer north-west to the main river, and the terminal moraine which would have marked the culmination of the advance has been lost to erosion. However, correlation is made with lateral moraine NV3 (see below).

The proglacial fluvial facies grades irregularly up into a return to slackwater conditions of shallow lacustrine deposition and marshy floodplain (unit 3). The unit comprises thin, finely laminated diatomaceous silts draped over the underlying gravels, and includes thin layers composed almost entirely of subfossil leaves. Towards the top of the unit, an unidentified coarse-grained red tephra forms a weathered, indurated layer characteristic of pre-settlement tephras. The unit represents shallow ponds on the surface of the till plain and indicates an absence of glacial influence on the site and a dominance of low-energy valley-floor processes and landscape stability.

A return to higher-energy conditions is marked by aggradation of the gravels of unit 4. These are interpreted as fluvial deposition in actively anastomosing channels, including abandoned channels infilled by finer sands and gravels containing resedimented H4 and (especially) the coarser-grained H3 tephra. The younger H3 tephra provides a maximum age because it must have already

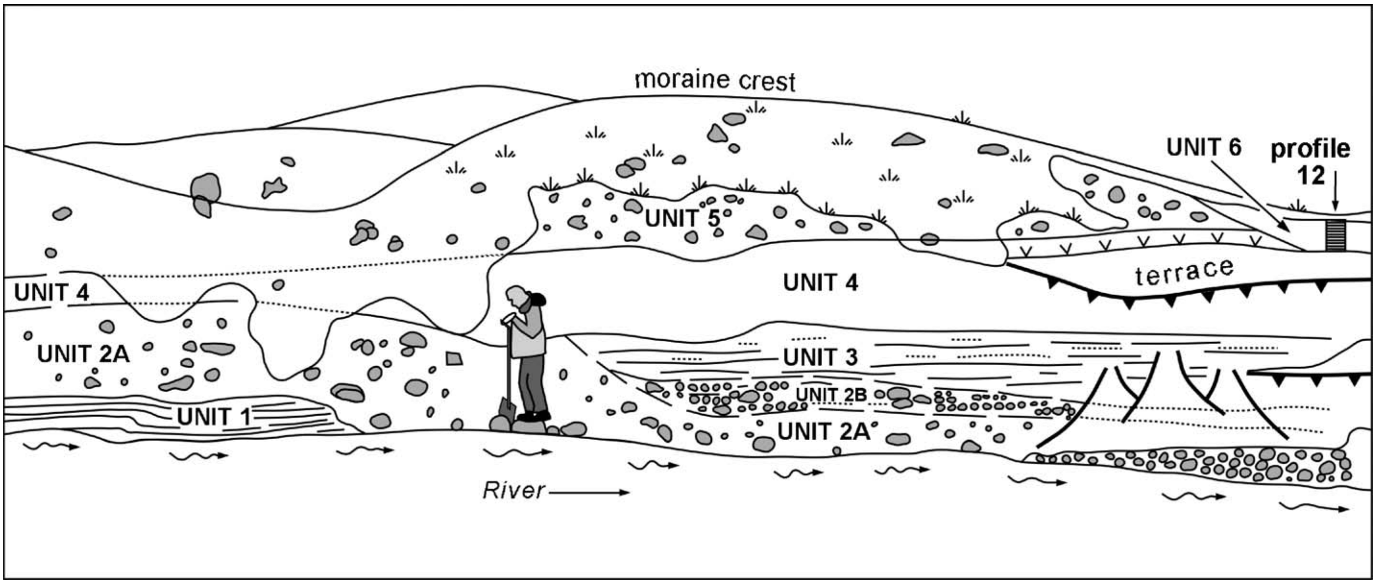

Fig. 8. Sketch of the riverbank section (Profile 13) exposing a cross section through the distal moraine NV2 at Norðvesturjökull. The location of profile 12 is indicated. The numbered sedimentary units are described in detail in Table 2. (Glacier advanced from left to right).

Table 2
Description and interpretation of sedimentological units in the Nordvesturjökull moraine NV2 section

Unit	Description	Interpretation
1	Laminated well-sorted silt with metre-scale lenses of medium gravel. Upper contact is a sharp erosional contact cross-cutting lamination.	Valley-floor floodplain environment with wandering channels and shallow lakes. Overridden by glacier advance.
2A	Coarse, poorly sorted and massive diamict of boulder gravel containing angular to subrounded volcanic clasts. Contains deformed rip-up clasts of unit 1 particularly near the base.	Basal till laid down after glacier advance across floodplain.
2B	Moderately sorted fine and medium gravel in beds and lenses.	Fluvially reworked top of unit 2A indicating glacier retreat and outwash aggradation across till plain.
—	—	Incision of river after glacier retreat.
3	Laminated diatomaceous silts including leaf beds. Contains indurated coarse dark red tephra near top of unit.	Valley-floor floodplain environment with wandering channels and shallow lakes.
4	Poorly to moderately sorted bedded gravel containing coarse imbricate clast-supported beds. Reworked Hekla-3 and Hekla-4 tephras occur in decimetre-thick sandy lenses.	Aggrading proglacial fan deposited as glacier readvanced towards the site. Reworked tephras in slackwater sediments (in abandoned channels?) date unit to post Hekla-3.
5	Poorly sorted, massive unweathered grey diamict forming NV2 terminal moraine ridge.	Glacial till marking second glacier advance. Post-depositional reworking of distal slope disturbed upper part of existing unit 6.
6	Bedded silty soil containing tephra sequence from Hekla-1104 to Hekla-4, centimetre-scale sand and gravel laminae, and palaeosol developed shortly before V870 tephra. Fine dark tephra below V870 tephra and all superjacent layers are disturbed by tight concordant folds with hinges dipping at low angles towards glacier.	Aeolian silt and tephra accumulating on outwash surface constructed after glacier retreat after deposition of unit 2. Preserved because of river incision, and unaffected by later glacier advance. Cryoturbated, particularly above fine dark tephra. Folding due to lateral pressure from solifluction on distal moraine slope (therefore moraine pre-dates V870 tephra).

been eroding from a nearby deposit to have become incorporated in the fluvial sediment. Above unit 4 lies the terminal moraine NV2, comprising the unit 5 till. The till forms the modern land surface, here forming a distinct moraine ridge extending round the entire margin of the former piedmont glacier lobe (Fig. 2). The moraine surface has a thin and discontinuous soil cover through which till boulders protrude. The moraine flanks are subdued and smoothed by solifluction, creep and heave of material from upslope. Distal to the moraine, a relict fan surface bears an aeolian soil cover (unit 6) which lies directly on the outwash gravels of unit 4. At this site, the tephra stratigraphy in Profile 12 (Fig. 5) records deposition since the H4 tephra 3834 ± 34 ^{14}C ka BP. The sequence contains the marker tephras H4, H3, V870, and H1104 in a disturbed sequence which includes four gravel layers, cryoturbated horizons, and a palaeosol immediately below the V870 layer, with tight folding affecting the upper profile above the highest of four gravel layers. EPMA of samples 12.4 and 12.5 (Fig. 6) confirm their field identification as V870 and H3, respectively.

The maximum and minimum ages of NV2 are provided by this sequence. The moraine overlies a reworked water-laid deposit containing the H3 and H4 tephras (unit 4), providing a maximum age of the overlying till of *c.* 2.9 ka BP. The minimum age is inferred by interpretation of the disturbed soil (unit 6) exposed in Profile 12. The gravel layers in the lower part of the profile, below the V870 tephra record the deposition of the NV2 moraine. The gravels are interpreted as localised washing of sediment from the distal slope of the adjacent moraine. Thus, the moraine predates A.D. 870. Folding in the upper profile disturbs, and therefore post-dates, the V870 and H1104 tephras. The folding is probably due to compression from upslope due to solifluction of the soil cover on the moraine in the post-Mediaeval period, i.e. during the LIA.

The timing of deposition of the Group 3 moraines is therefore poorly constrained. The most likely period in which it occurred is the "Subatlantic" period of climatic deterioration between *c.*2.0 and 2.6 ka BP (Grove, 1988; van Geel et al., 1996), manifested in Iceland by ecological changes (Einarsson, 1963) and solifluction activity (Kirkbride and Dugmore, 2005).

4.4. Group 4—moraines bracketed by the Hekla-4 and Hekla-3 tephras

Profile 7 was a large trench in the distal slope of VJ5 (Fig. 9). The thick soil profile contained a highly indurated deposit of V870, below which a discontinuous layer of till boulders lay between the H4 and H3 tephras (Fig. 5). Both layers were confirmed by EPMA (Fig. 6, samples 7.2 and 7.3). One interpretation is that the moraine was formed prior to H4 but the distal slope was disturbed at a later date, to cause the boulders to fall down the slope. However, the sheltered location of the site and the size of the boulders precludes local run-off as a possible cause. The trench has dissected an apron of till clasts which rolled down the front of the moraine during its construction to come to rest on older soil. The presence of these clasts between H3 and H4 mean that these tephra layers provide minimum and maximum limiting dates for the moraine of *c.* 3.0 and *c.* 4.2 cal ka BP.

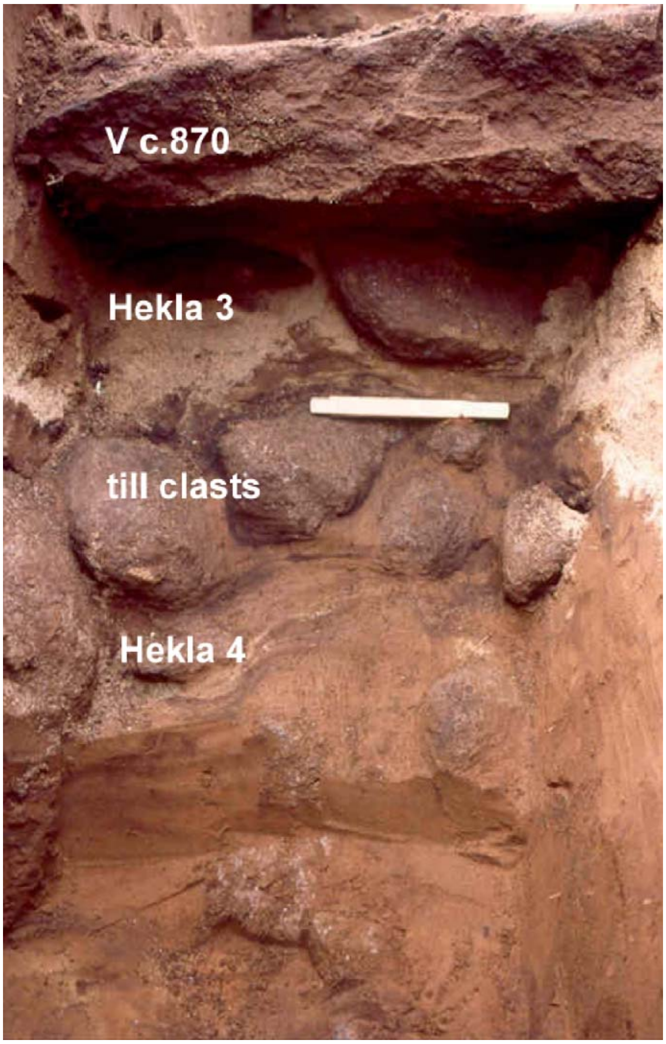

Fig. 9. Photograph of Profile 7 in moraine VJ5 showing till boulders from the moraine between the H3 and H4 tephras. The layers are disturbed by cryoturbation. See Fig. 5 for stratigraphic log.

4.5. *Group 5—moraines predating the Hekla 4 tephra (c. 3.8 ka BP)*

At Vesturjökull, four soil profiles in the lateral moraine VJ4 showed different basal tephra layers at different places on the moraine. The moraine had been affected by meltwater from the later Group 1 and Group 2 advances, and localised undercutting and slumping of its flanks has occurred. Three profiles contain a distinctive silicic tephra identified as H4 (EPMA sample 2.1, Fig. 6) which provides the minimum age for the moraine. Moraine fragment VJ6 is dated by the basal tephra layer in Profile 8 (Figs. 5 and 10). This deep trench revealed an unbroken sequence of tephras back to H4. The moraine against which this sediment is banked therefore predates H4, and remained undisturbed when Vesturjökull deposited the VJ5 moraine to the east. As in Profile 12, the upper part of the soil profile is highly disturbed above the V870 tephra. VJ4 and VJ6 are therefore fragments of the same original moraine.

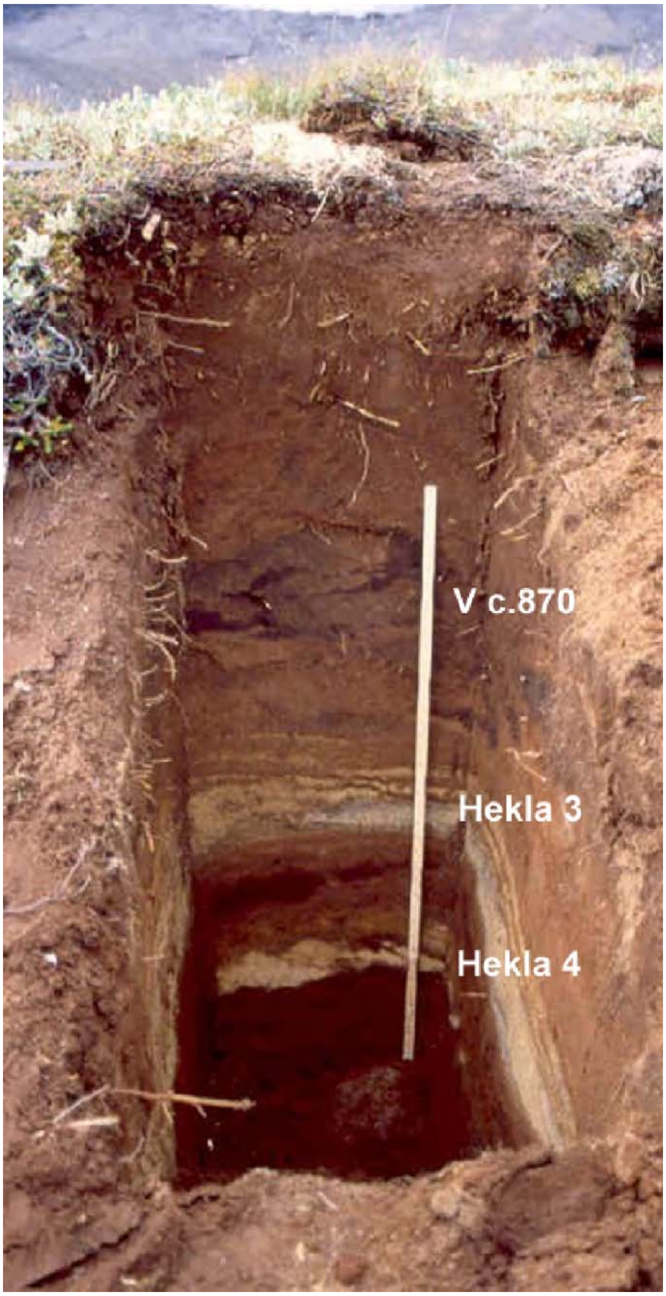

Fig. 10. Photograph of Profile 8 in moraine VJ6 showing the H4 tephra overlying till boulders. See Fig. 5 for stratigraphic log.

At Nordvestujökull, till deposition prior to H4 laid down the lower till (unit 2) in the riverbank section. NV3 provides the only possible correlative with the lower till, being the only surviving moraine distal to NV2. The soils on the moraine are severely disturbed and do not provide a close limiting age. The oldest tephra (V870) is demonstrably unrepresentative of the moraine age because the moraine lies distal to NV2 and should be much older. Notwithstanding uncertainties over the age of the moraine, the stratigraphic position of the buried till is unequivocal. The erosional contact between the till and the laminated silts of unit 1 suggests that the till represents the earliest

Neoglacial glacial advance across the floodplain of Sanddalur at some time prior to 4.2 cal ka BP.

4.6. *Undated moraines bracketed by dated moraines*

Three pre-Group 1 moraines mapped on Fig. 3 cannot be closely dated by tephrochronology. The best available dates for these moraines are the limiting ages provided by neighbouring dated deposits. Both VJX and NVX are interpreted as moraines overridden by Group 1 advances. From its position, moraine VJX is younger than the early 18th century moraine VJ2. Its age is thereby constrained to the LIA, possibly a correlative of moraines in south Iceland dated to between A.D. 1721 and 1755 (Kirkbride and Dugmore, 2001a). Alternatively, a late 18th or early 19th century date would correspond to the very cold decade of the A.D. 1780s (Ogilvie, 1992). NVX can only be dated as older than Group 1 but probably younger than Group 3, a period of time including the earlier part of the LIA, but also a period in which glacier advances elsewhere around the North Atlantic have been dated to just before and after the "Mediaeval Warm Period" (Grove and Switsur, 1994). Finally, moraine VJ3 at Vesturjökull predates Group 2 but postdates Group 3 by its position. Again, a Mediaeval age is a possibility for this moraine.

5. Discussion

5.1. *Regional significance of the Hrútfell moraines*

The composite sequence of glacier advances at Hrútfell is presented in Table 3. Hrútfell Group 1 moraines have many late LIA correlatives in the period *c*. A.D. 1880–1920 (e.g. Evans et al., 1999; Bradwell, 2001; Caseley and Dugmore, 2004; Kirkbride and Dugmore, submitted). Group 2 moraines represent the LIA maximum at this site, probably A.D. 1690–1700 (within the Maunder Minimum) though moraine VJ2 may have been formed between 1721 and 1766. Group 2 moraines correlate with an apparent LIA maximum advance predating the Katla A.D. 1721 tephra at both Steinsholtsjökull and Gígjökull in the south (Kirkbride and Dugmore, 2001a, submitted). These, and other steeper local glaciers in Iceland (Björnsson, 1979), also constructed moraines in the 1740s. Group 3 moraines broadly fall into Einarsson's (1963) "Late Bog Period" of the Subatlantic, a period of variably cooler and moister climate in the region associated with glacier advances in south and eastern Iceland (Guðmundsson, 1997). There is widespread evidence for periglacial disturbance to soils in this period, as exemplified by soil profiles at Hrútfell (e.g. The post-H3 sequences in profiles 8 and 12) and elsewhere (Sharp and Dugmore, 1985; Hirakawa, 1989; Kirkbride and Dugmore, 2005). Marine sediments record cooler oceanic conditions around Iceland at this time (Andrews et al., 2001). Group 4 moraines correlate with the Vatnsdalur II advance in northern Iceland at *c*.3.0–3.2 ka BP (Stötter et al., 1999) and with a pronounced cooling in sea surface temperatures (Eiríksson et al., 2000; Andrews et al., 2001) and lowering of the treeline in the north (Wastl et al., 2001). The onset of "Neoglaciation" after *c*. 5 ka BP is marked by Group 5 moraines, broad correlatives with the Vatnsdalur I (*c*. 4.7 ka BP) advances in Tröllaskagi and Kerlingarfjöll (Stötter et al., 1999; Kirkbride and Dugmore, 2001b).

5.2. *Contrasting responses between steep mountain glaciers and large ice cap lobes*

Correlation of this central Icelandic moraine sequence with northern and southern glaciers adds weight to arguments in favour of a classic "Neoglacial" model of Holocene glaciation across Iceland (Guðmundsson, 1997). The study area also reveals a systematic difference in moraine chronologies between the steep, local glaciers and the large ice cap lobes of Langjökull. This contrast has long been recognised in Iceland (Björnsson, 1979) and indicates different dynamic responses between the two glacier types in which local glaciers reached their Holocene maxima in

Table 3
Summary of glacier advances at Hrútfell and correlations with north and south Iceland

Hrútfell advances	Northern Iceland[a]	Southern Iceland
Group 1 A.D. 1880–1920	Widespread late LIA limits	Widespread late LIA limits
Group 2 A.D. 1690–1740	Not recorded	Outlets of Eyjafjallajökull[b], Vatnajökull[c], Öraefajökull[d,e]
Undated NVX and VJ3 moraines	Baegisárdalur II or Barkárdalur II?	Sólheimajökull?[f]
Group 3 Subatlantic *c*.2.0–2.5 ka BP	Barkárdalur I	Öraefajökull[d,e], Snaefell[g],outlets of Eyjafjallajökull[h]
Group 4 pre- H3, post-H4, *c*.3 ka BP	Vatnsdalur II	Öraefajökull[d,e], Sólheimajökull[f]
Group 5 pre-H4, post H5, *c*. 4-5ka BP	Baegisárdalur I or Vatnsdalur I	Öraefajökull[d,e], Sólheimajökull[f]

[a] Stötter et al. (1999).
[b] Kirkbride and Dugmore (2001a).
[c] Bradwell (2001).
[d] Guðmundsson (1998a).
[e] Guðmundsson (1998b).
[f] Dugmore (1989).
[g] Thórarinsson (1964).
[h] Kirkbride and Dugmore (unpublished data).

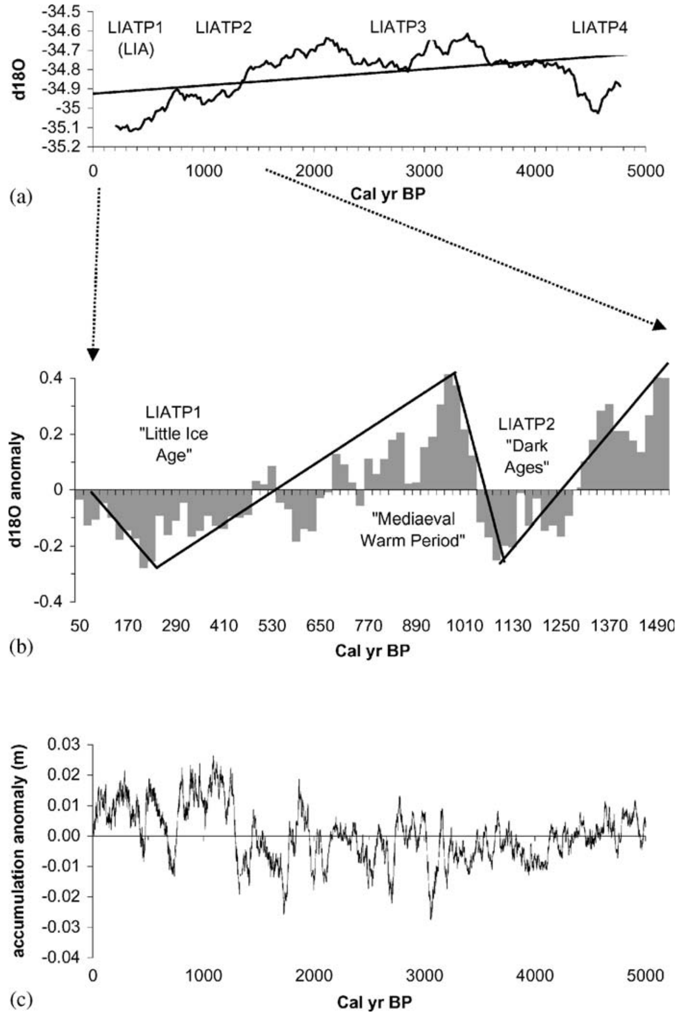

Fig. 11. Climate proxies from the GISP2 ice core in central Greenland. (a) The last 5000 years of the δ^{18}O record smoothed with a 500-year filter. (b) Deviations from the mean value of the δ^{18}O record for the last 1500 years showing bidecadal changes within the period of the "Mediaeval Warm Period" and the "Little Ice Age". (c) Fifty-year running mean of annual accumulation (Cuffey and Clow, 1997) expressed as deviations from the mean value for the last 5000 years.

the early to mid-Neoglacial period, up to four millenia before the large ice caps. The difference in response times of between 10^1 and 10^3 years for the range of glacier types found in Iceland (Jóhannesson, 1986; Jóhannesson et al., 1989) is analogous to Haeberli's (1995) explanation of size-related responses of Swiss glaciers, in which small glaciers respond to a decadal timescale of climate signal while large valley glaciers filter and smooth short-term climatic "noise" to record century-scale climate variation. Size-related differences in Icelandic glaciers will cover an even wider spectrum of responses. Expansion of the largest ice caps until one century ago mirrors the general cooling trend over the last 5000 years found in sea-floor sediments on nearby continental shelf (Eiríksson et al., 2000; Smith et al., 2005), while high-frequency oscillations of small glaciers may reflect forcing by short-term variability in atmosphere/ocean circulation (Kirkbride, 2002) and correspond to the well-known sea ice record (Bergthórssen, 1969; Ogilvie and Jónsson, 2001).

The high-resolution palaeoclimate record from the GISP2 ice core has been shown to have a fair correlation to Icelandic climate history (Barlow, 2001) with well-defined synoptic connections (Barlow et al., 1997). The record for the last 5000 years, when smoothed with a 500 year filter (Fig. 11(a)), shows greater depletion of δ^{18}O (a proxy for air temperature) over the last 3.5 millenia indicating a long-term cooling trend, represented in its most general form by the linear best-fit line through the last 5 millenia in Fig. 11(a). This trend may be read as a proxy for the long-term growth of slowly responding Icelandic ice caps such as Langjökull. At higher resolutions, the bidecadal variations in δ^{18}O within the MWP and LIA (Fig. 11(b)) can be read as the response scale of small, steep Icelandic glaciers such as those draining the Regnabuða-jökull ice cap. The rapidity of climate fluctuations within the LIA (Ogilvie and Jónsson, 2001) allows only the fast-responding glaciers to record this timescale of variability as multiple moraine sequences. The moraine chronologies revealed by each glacier type appear to be predetermined by the scale of the glacier system, with small mountain glaciers able to respond to the decadal climatic variability which the large ice caps filter and aggregate.

5.3. *"Little Ice Age"-type periods in the North Atlantic region*

The term "Little Ice Age Type Event" (LIATE) has been introduced by Wanner et al. (2000) to refer to quasi-regular glacier advances at intervals of 200–400 years in the Swiss Alps. The decadal-scale climate and mass balance variability which characterises the LIA (Ogilvie and Jónsson, 2001) allows a similar approach to be applied to Icelandic glaciers. The Hrútfell moraine chronology is combined with comparable chronologies from Eyjafjallajökull (Kirkbride and Dugmore, submitted), Kerlingarfjöll (Kirkbride and Dugmore, 2001b), and Sólheimajökull (Dugmore, 1989) to synthesise a composite sequence of LIATEs for southern and central Iceland (Table 4).

All glacial chronologies are partial representations of a complex climatic signal, and involve loss of evidence with time (Kirkbride and Brazier, 1998). Therefore, a comparative set of *potential* LIATEs has been derived from negative anomalies in the bidecadal δ^{18}O record from the GISP2 ice core in central Greenland for the last five millenia (Fig. 11 and Table 4). Not all of these isotopically low spikes may have resulted in advances of Icelandic glaciers, because the complex synoptic climatology of the NW Atlantic means central Greenland and Iceland share common climatic deviations in only 60–70% of years at this temporal resolution (Barlow, 2001). They do, however, provide a complete record of cold decades in Greenland, a proportion of which can be expected to correlate with glacier advances in Iceland. That we have found eight such periods in the Hrútfell moraine record out of the 29 LIATEs nominally

Table 4
Little Ice Age Type Events (LIATEs) in Iceland and Greenland. Icelandic LIATEs are based on the moraine chronologies from Hrútfell (this study) and Eyjafjalljökull (Kirkbride and Dugmore, submitted)

Icelandic LIATEs			Tephra isochrones	GISP2 LIATEs	
Period	LIATE	Date		LIATE	Spike decades
	1	AD1860-1920	Katla 1918	1	AD 1860–1880
			Hekla 1766	2	AD 1780–1800
"LIA"	2	AD 1680-1780	Katla 1721	**3**	**AD 1700–1740**
				4	AD 1660–1680
				5	AD 1580–1620
				6	AD 1520–1560
			Hekla 1300	**7**	**AD 1300–1360**
	3	AD 1180-1200		8	AD 1180–1200
			Hekla 1104	9	AD1040–1080
"Dark Ages"	4	AD 700-900	Landnam c.AD 870	10	AD 760–820
				11	AD 720–740
				12	AD 640–700
	5	*c.*1600 BP		13	AD 500–520
				14	AD 360–380
				15	**AD 180–220**
	6	*c.* 2000-2500 BP		16	BP 2150–2170
				17	BP 2270–2310
Subatlantic				18	BP 2450–2470
				19	BP 2630–2670
				20	BP 2770–2810
	7	*c.* 3000 BP	H3 *c.* 3300 cal yr BP	**21**	**BP 2990–3030**
				22	BP 3370–3390
				23	BP 3570–3590
				24	**BP 3850–3910**
Early Neoglacial	8	*c.* 4500-5000 BP	H4 *c.* 4200 cal yr BP	25	BP 4350–4390
				26	BP 4430–4450
				27	BP 4610–4630
				28	**BP 4730–4810**
				29	BP 4990–5010
			↓H5 *c.* 6200 cal yr BP		

Shaded areas mark prolonged periods of reduced isotopic values in the GISP2 record ("Little Ice Age Type Periods", LIATPs). Bold type denotes isotopically low spikes immediately following major declines into LIATPs.

identified in the Greenland δ^{18}O record will reflect, firstly, the censoring of the Icelandic moraine record by erosion; secondly, deposition of multiple moraines within parcels of time bound by tephra isochrones; and thirdly, the possible lack of correspondence between bidecadal-scale cold periods in Greenland and Iceland.

Examination of the GISP2 record shows that LIATEs cluster within longer periods of depressed isotopic values, here termed "Little Ice Age Type Periods" (LIATPs). LIATPs are marked by sharp downturns in δ^{18}O values at *c.* 0.75, 1.40, 3.05 and 4.70 cal BP., with minima at *c.* 0.35, 1.00, 2.85–2.40 and 4.55 cal BP. At this coarser timescale, a greater synchrony across the North Atlantic region may be expected. The most recent LIATP is the LIA itself, while LIATP2 and LIATP3 broadly correspond to the loosely termed "Dark Ages" and "Subatlantic" periods. The Subatlantic period, originally defined on botanical grounds, appears to represent the vegetational response to a series of six LIATEs between 3.0 and 2.0 cal BP. LIATP 4 has no stratigraphic name, so here is informally termed the "early Neoglacial". Group 1 and 2 moraines at Hrútfell correspond to Icelandic LIATEs 1 and 2 within LIATP 1, groups 3 and 4 to LIATEs 6 and 7 within LIATP 3, and group 5 to LIATE 8 within LIATP 4. At Kerlingarfjall, 25 km ESE of Hrútfell, Kirkbride and Dugmore (2001b) dated moraines to LIATPs 1 and 4. In the south of Iceland, moraines at Gígjökull and Steinsholtsjökull date from LIATPs 1 and 2 (Kirkbride and Dugmore, submitted) while at Sólheimajökull moraines fall into all four LIATPs (Dugmore, 1989; Guðmundsson, 1997).

LIATPs 1, 2, 3 and 4 all correspond to periods of increasing EOF1 polar circulation index from the GISP2 ice core (O'Brien et al., 1995). LIATPs 1, 3 and 4 also correspond to periods of cooler sea water on the North Iceland Shelf (Castañeda et al., 2004). The GISP2 accumulation record (Fig. 11(c)) indicates increased accumulation during all four LIATPs, especially during the last 1300 years (LIATPs 1 and 2). These last cool intervals may have been particularly favourable for glacier growth due to increased precipitation as well as reduced temperature. If Icelandic glaciers were in phase with Greenland climate at the century scale, the apparently greater LIA extents of glaciers in many coastal locations compared to earlier LIATPs may reflect enhanced precipitation. However, evidence is emerging from several studies for the fragmentary survival of pre-LIA moraines at forelands throughout Iceland. The Hrútfell chronology, along with evidence from Kerligarfjöll (Kirkbride and Dugmore, 2001b) and Snaefell (Kirkbride and Dugmore, 2005), indicate a greater preservation potential of pre-LIA moraines in interior locations in Iceland.

The significance of earlier LIATPs has been neglected while scientific attention has been focused on the detail of the LIA itself (Grove, 1988, 2001, 2004; Ogilvie and Jónsson, 2001). The nested event/period approach adopted here provides a workable stratigraphic nomenclature within which regional correlations can be made at different temporal resolutions. It reveals considerable synchrony of glacier advances within central, southern and northern Iceland, and shows the LIA to be the most recent in a series of "Neoglacial" cool periods affecting landmasses bordering the North Atlantic Ocean.

6. Conclusions

1. This study shows that it is possible to obtain moraine chronologies which are well constrained by tephrochronology even from glacier forelands at a relatively high altitude in the Icelandic interior.
2. Five main groups of glacier advances are identified for the first time from a site in central Iceland. These occurred around *c*. 4.5–5.0, *c*. 3.0–3.5 and *c*. 2.0–2.5 ka BP, *c*. A.D.1690–1740, and in the late 19th/early 20th century. Preserved evidence indicates that glaciers in the LIA were most extensive in the decades before A.D.1721, in keeping with glaciers of similar type in south Iceland. Preservation potential of older deposits appears to be greater in interior locations.
3. The contrasting moraine chronologies of small, steep glaciers and large, gentle ice cap lobes are marked. This is interpreted as a manifestation of a dynamic difference in glacier response to climate variability. These differing dynamic responses mean that the temporal distribution of moraines at any glacier will be partly predetermined by the glacier type. The forelands of small glaciers generally have greater preservation potential and their deposits record higher-frequency climate signals than the margins of large ice-cap outlet glaciers.
4. Century-scale periods of glacier expansion, termed LIATPs, occur synchronously between northern, central and southern Iceland. Decadal-scale advances, termed LIATEs, also appear to be recorded synchronously in glacier forefields across Iceland, although local differences in glacier response and deposit preservation may influence which LIATE occurs as the local LIA maximum. This study adds to an emerging pattern of correlative glacier advances conforming to the classic "Neoglacial" model of glaciation.

Acknowledgements

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Appendix A. A note on place names in the study area

There is ambiguity about the correct names for the study glaciers. The icecap covering Hrútfell is named Regnabuðajökull on the most recent 1:250,000 topographic maps, though on earlier maps only the mountain Hrútfell was named. The icecap is called Hrútafell on the 1945 map, and the icecap Hrútafellsjökull in the Icelandic glacier inventory (Williams, 1986), which also refers to the four outlet glaciers as Norðurkinn E, Norðurkinn M, Norðurkinn W and Norðvesturjökull. Alternative names for the last three glaciers are given as Miðjökull, Vesturjökull, and Norðvestur (*sic*). Here, we adopt the standard cartographic name Regnabuðajökull for the ice cap, while preferring the more independent names Norðurkinn- Eystri, Miðjökull, Vesturjökull, and Norðvesturjökull for the four outlet lobes. Finally, the valley draining the eastern margin of Langjökull in the study area, and bounding the western slopes of Hrútfell, is referred to as Þjófadalur on the early map, but Sanddalur on the most recent map. Here, we adopt the most recent name.

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