A 36 Ky record of iceberg rafting and sedimentation from north-west Iceland

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Evidence from north-west Iceland's shelf and fjords is used to develop a scenario for environmental change during the last 36 cal Ky. The retreat history of the Iceland Ice Cap during the last deglaciation is delineated through lithofacies studies, carbon analyses and magnetic susceptibility, and studies of ice-rafted debris (IRD) in sediment cores. Sedimentological data from lake Efstadalsvatn, Vestfirdir peninsula, trace the glacier retreat on land. In two of the high resolution shelf cores we detect near continuous IRD accumulation from 36 to 11 cal Kya. However, IRD is absent in the cores from ca. 22 to 19 cal Kya, possibly indicating more extensive landfast sea ice conditions. All cores show intensified IRD during the Younger Dryas chronozone; the fjord cores show a continuous IRD record until 10 cal Kya. Magnetic susceptibility and carbon analyses from Efstadalsvatn reveal the disappearance of local ice in the basin just before 10.5 cal Kya. No IRD was detected in the sediment cores during 10 to ~4 cal Kya. Some indication of cooling occurs between 4 and 3 cal Kya, with a fresh input of IRD in fjord cores after 1 cal Kya.

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Most reconstructions of the Iceland Ice Cap during the Last Glacial Maximum (LGM) describe Iceland as heavily glaciated and portray a single ice cap covering most of the island. However, there is some consensus that the Vestfirdir peninsula (VP) hosted an independent ice cap during the LGM with ice streams and outlet glaciers flowing away from an ice divide above the central parts of the peninsula (e.g. Hjort et al. 1985; Bourgeois et al. 2000; Stokes & Clark 2001). Ice streams are pictured flowing out major fjords, such as Ísafjardardjúp and along Djúpáll trough, but direct evidence for the extent of the ice streams has been lacking. New evidence from marine and terrestrial studies indicates that the ice extent on the VP was more restricted during the LGM than previously believed and that it did not extend across the Djúpáll trough. Andrews et al. (2002) base their conclusion of the LGM extent on marine sediment cores taken from the Djúpáll trough and Norddahl & Pétursson (2002) on gradients of raised shorelines in the VP.

In this paper we use new sedimentological data from the VP and the adjacent shelf to delineate the retreat pattern of the VP glacier from the LGM through the deglaciation and early Holocene. We base our story on seismic profiles from the Djúpáll–Ísafjardardjúp system and proxies in sediment cores collected during cruises in 1997 and 1999, and compare these with proxies from the lake Efstadalsvatn, VP (Fig. 1).

The VP shelf is dominated by warm, saline water of Atlantic origin, transported northward via the Irminger Current (Fig. 1). This branch of Atlantic Water meets the colder East Greenland Current just west of the VP and the East Ice-

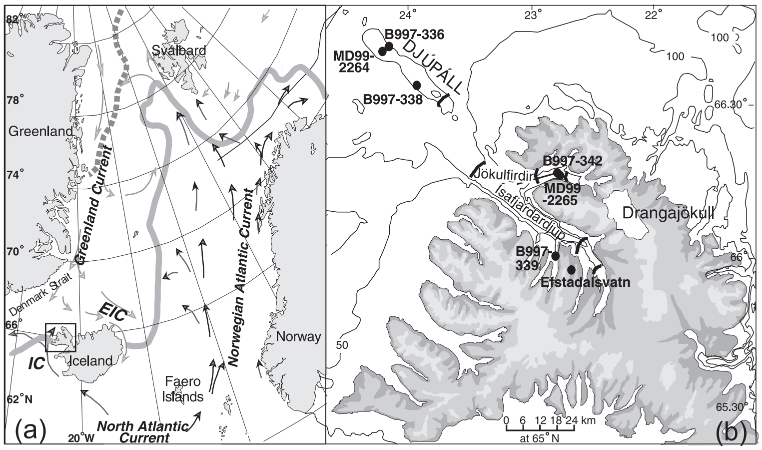


Fig. 1. (a) The surface ocean circulation around Iceland and in the North Atlantic. The thick dashed line indicates typical sea ice extent in a mild summer; the thick grey line shows the typical extent of ice in a severe winter. IC = Irminger Current, EIC = East Icelandic Current. (b) Bathymetry of the north-west Iceland shelf, topography of the Vestfirdir peninsula and core locations (black dots). Inferred moraines revealed from seismic measurements are shown with thick black lines.

landic Current just east of the VP. This area is extremely sensitive to changes in the strength of the opposing surface currents, manifested in the formation of heavy sea ice on the VP shelf and cooling of the land areas during years of stronger polar current inflow (e.g. Dickson et al. 1988).

Extensive seismic reflection profiles from the Djúpáll–Ísafjardardjúp system show ca. 40 m thick sediment in Djúpáll, but more than 100 m thick in the outer part of Ísafjardardjúp. In Jökulfirdir the sediment thickness is 25 - 35 m. Major transverse ridges were identified from the seismic profiles as being of morainic origin (Thors & Helgadóttir 1999).

Cores used for this study lie on a transect from Djúpáll (B997-338, -336, MD99-2264) to Jökulfirdir (B997-342, MD99-2265) and Skötufjördur (B997-339) (Fig. 1). We also use some correlative records from Efstadalsvatn, to aid in the reconstruction of ice retreat and the Holocene development of the area. The lake is located in a narrow, glacially scoured valley about 10 km south-east from B997-339.

Uncorrected radiocarbon accelerator mass spectrometry (AMS) dates used in this paper are shown in Table 1 (see ^{14}C dates from B997-336/338 in Andrews et al. 2002). The AMS ^{14}C dates show that the cores used in this study contain sediment accumulating over the last 36 cal. Ky, constituting the longest continuous sedimentary record obtained so far from the Iceland shelf. The oldest record (34 600 ^{14}C yrs) is from Djúpáll and at least the last 11 000 ^{14}C yrs have been recovered from the fjord and the lake systems. The Vedde and Saksunarvatn tephras have been geochemically identified in many of these cores and provide a regional isochron at ca. 10 300 ^{14}C yrs BP and 9000 ^{14}C yrs BP, respectively (Bard et al. 1990; Grönvold et al. 1995).

Radiocarbon AMS dates from MD99-2264 are concentrated over the interval from 9430 ± 70 to 12 080 ± 90 ^{14}C yrs except for the basal date at 33 150 ± 1750 ^{14}C yrs. We are aware of the lack of adequate dating control of this core. However, we believe we can correlate the sedimentary record with that of B997-338/336 based on tephra layers, the seismic profile and magnetic susceptibility record. Similarly, we have used the seismic profile and the near identical magnetic susceptibility record of MD99-2265 and B997-342 to correlate the two records from Jökulfirdir.

The top of the Efstadalsvatn core was lost on recovery, which resulted in termination of the record at around 3200 ^{14}C yrs BP (Table 1; Caseldine et al. in press).

Methods

X-radiographs were made of each core, photos were taken and lithofacies were described visually. The magnetic susceptibility was measured both as a whole core volume susceptibility (vol MS) and as mass susceptibility (mass MS) of known volume (10 cc) using a Bartington MS2 meter. MS commonly gives a measure of the magnitude of terrestrial input into the marine or lacustrine environment, showing higher values during periods of more intense terrestrial erosion (Walden et al. 1999). However, the MS signal can be diluted by the carbonate or total carbon content, showing lower values.

Samples for total carbonate/carbon analysis (TC) were run on a CM5120 furnace device (combusted to 950 °C) and then measured on a CO_2 coulometer with a detection limit of 0.01 wt.%. The carbonate content reflects variations in the net productivity within the marine (or carbon in lacustrine) environments (Thórdardóttir 1984; Syvitski et al. 1990).

To portray the ice-rafted detritus (IRD) flux on the shelf and fjords over the last 36 Ky, X-radiographs of the cores were used to count clasts ≥ 2 mm. This is a modification of a method originally developed by Grobe (1987) and used extensively on cores from the East Greenland margin (Stein et al. 1996; Andrews et al. 1997).

A seismic reflection profile of the Djúpáll trough was obtained from the Woods Hole Oceanographic Institution SUBSCAN chirp profiling system in 2001 and resulted in a high resolution record of the trough sediments (Fig. 2a; Ólafsdóttir 2002). This profiling system works on the frequency of 0.5 - 16 kHz and gives a much better resolution than the 3.5 kHz seismic profiles previously available (Andrews et al. 2002).

Results

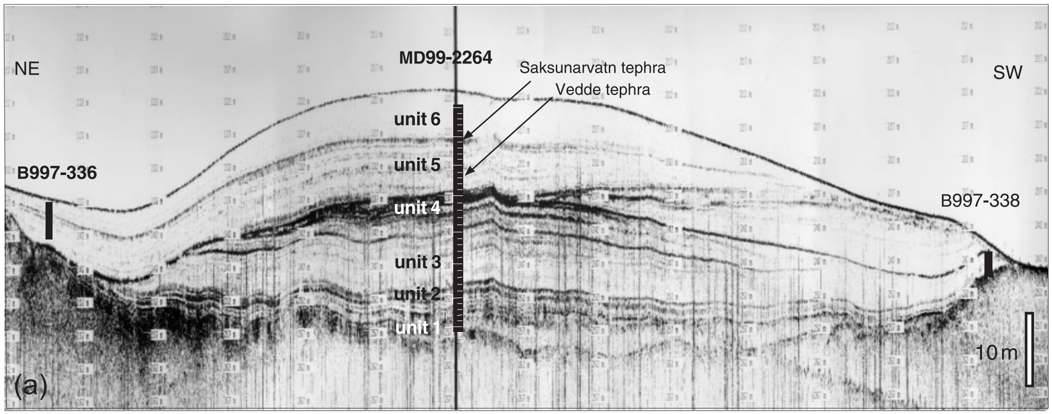
Djúpáll—MD99-2264, B997-336 and -338

Andrews et al. (2002) show a detailed figure of the site locations for cores B997-336/-338. The chirp profile transverses the trough where cores MD99-2264 and B997-336 were taken, but B997-338 is projected on the profile (Figs. 1, 2a).

Two prominent seismic reflectors at ca. 7 and 15 m coincide with the Saksunarvatn tephra and distinct erosional surfaces, respectively. Based on

Table 1. Uncorrected radiocarbon dates used in this paper. Calibrated ages were calculated using the Calib 4.3 radiocarbon program (Stuiver et al. 1993). The age older than 22 Ky in core MD99-2264 was calibrated by adding a 2000 year correction (see Andrews et al 2002). Problems of conversion, particularly on dates older than 20 Ky, are discussed in Andrews et al. (2002). Detailed descriptions of dates obtained from cruise B997 are available in Smith & Licht (2000) and these can also be seen at: //instaar.colorado.edu/ other/download/OP54_DLIX.pdf. (See also ^{14}C dates from B997-336/338 in Andrews et al. 2002).

Core	Depth (cm)	Date (^{14}C yrs BP)	Calibrated age BP	Error range	Lab. number	Material dated
MD99-2264	476	9430 ± 70	10071	9861 - 10281	AAR-5490	mollusc
	500	~9000 ± 80	10180 ± 60	Saksunarvatn ash		
	576	9670 ± 70	10432	10267 - 10597	AAR-5491	mollusc
	643	9850 ± 75	10573	10336 - 10809	AAR-5492	mollusc
	895	10500 ± 80	11540	11190 - 11890	AAR-5493	mollusc
	1169	11170 ± 90	12657	12412 - 12902	AAR-5494	mollusc
	1339	12080 ± 90	13614	13415 - 13813	AAR-5495	mollusc
	3781	33450 ± 1750	?35400	?	AAR-5496	mixed benthics
MD99-2265	26	900 ± 33	504	457 - 550	AAR-7033	mollusc
	137	2425 ± 50	2053	1963 - 2142	AAR-5497	mollusc
	288	4520 ± 50	4705	4610 - 4799	AAR-7034	mollusc
	324	4875 ± 50	5166	5044 - 5288	AAR-5498	mollusc
	357	5385 ± 55	5756	5648 - 5864	AAR-7035	mollusc
	452	6690 ± 60	7208	7146 - 7270	AAR-7036	mollusc
	622	7590 ± 65	8040	7943 - 8137	AAR-7037	mollusc
	731	8415 ± 60	8909	8845 - 8973	AAR-5499	mollusc
	1055	9420 ± 75	10070	9847 - 10293	AAR-7039	mollusc
	1069	~9000 ± 80	10180 ± 60	Saksunarvatn tephra		
	1148	9660 ± 65	10427	10273 - 10582	AAR-7040	mollusc
	1466	10740 ± 80	11355	11086 - 11624	AAR-7041	mollusc
	1687	10920 ± 90	12374	11964 - 12784	AAR-5500	mollusc
	1721	11660 ± 90	13176	12995 - 13358	AAR-7042	mollusc
B997-342	440	9279 ± 80	10018	9807 - 10229	AA-31748	mollusc
B997-339	1.25	1450 ± 65	991	927 - 1054	AA-31234	*Elphidium* exc
	132	8415 ± 65	8909	8844 - 8974	AA-31235	*Nonionellina* lab
	170	~9000 ± 80	10180 ± 60	Saksunarvatn tephra		
	359	9815 ± 70	10560	10323 - 10796	AA-31236	mollusc
	527	10450 ± 85	11410	11168 - 11653	AA-26518	mollusc
Efstadalsv.	24	3895 ± 50	4334	4258 - 4410	AAR-3714	twig
	132	7065 ± 65	7882	7792 - 7941	AAR-4340	bulk
	200	~9000 ± 80	10180 ± 60	Saksunarvatn tephra		
	203	9050 ± 70	10210	9974 - 10360	AAR-4341	bulk
	259	9470 ± 70	10819	10579 - 11059	AAR-4342	bulk



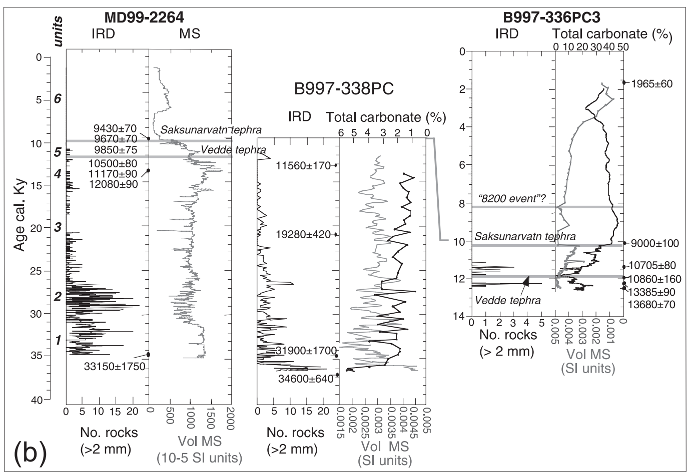


Fig. 2. (a) Chirp profile of the Djúpáll trough with core locations (see Fig. 1 for profile location). Also shown are lithofacies units from core MD99-2264, discussed in the text. (b) Magnetic susceptibility, carbonate content and IRD records in the Djúpáll cores (MD99-2264, B997-338 and B997-336). Also shown are lithofacies units for core MD99-2264, the location of the Vedde and Saksunarvatn tephras in the cores. The inferred location of the 8.2 cal. Kya event is shown for core B997-336. Available uncorrected ^{14}C dates are projected on the logs.

lithofacies, MS and the chirp profile (Fig. 2), the Djúpáll sediment can be divided into 5 units.

Unit 1 (35 - 31 cal. Kya) comprises a stiff, massive diamict, loaded with IRD. Its appearance and high but relatively stable vol MS points to a deposition close to or at an ice margin.

The fluctuating MS of unit 2 (31 - 26 cal. Kya) can be partly explained by fining-up sequences of sand, silt and clay. Load casts are common along bedding planes but sand layers decrease towards the top of the unit, which is still loaded with IRD. This rhythmic nature reflects high-energy, ice-proximal setting and formation of turbidites (Gilbert 1983; Ó Cofaigh & Dowdeswell 2001), although the upward fining in grain size exhibits a progressive distance from the ice margin.

Unit 3 (26 - 15 cal. Kya) shows relatively high, but much more stable, MS than the underlying unit. The sediment is massive to faintly laminated silty clay with numerous IRD. The unit reflects glacial marine sedimentation where icebergs were free to drift most of the time. However, the interval of no IRD in B997-338 (22 - 21 cal. Kya) may indicate a period of landfast sea ice cover which inhibited any iceberg rafting over Djúpáll. No shells were found in this interval, indicating unfavourable living conditions.

Unit 4 (15 - 11 cal. Kya) contains layering of fining upward sequences of fine sandy silt. Considerable changes show up in the MS and IRD is still apparent, although decreasing up-unit. Found in the core at 11.83 m, the Vedde tephra shows only as a weak reflector in the chirp profile. Several strong seismic reflectors detected in the unit coincide with erosional surfaces and turbidites and are tentatively explained by changing bottom current pattern and possibly sea level fluctuations.

Unit 5 contains the last 11 cal. Ky. The Saksunarvatn tephra coincides with a marked drop in MS at 5 m (see Andrews et al. in press) but the sediment is mostly massive, fine-grained sand with abundant shells. Increased carbonate up-

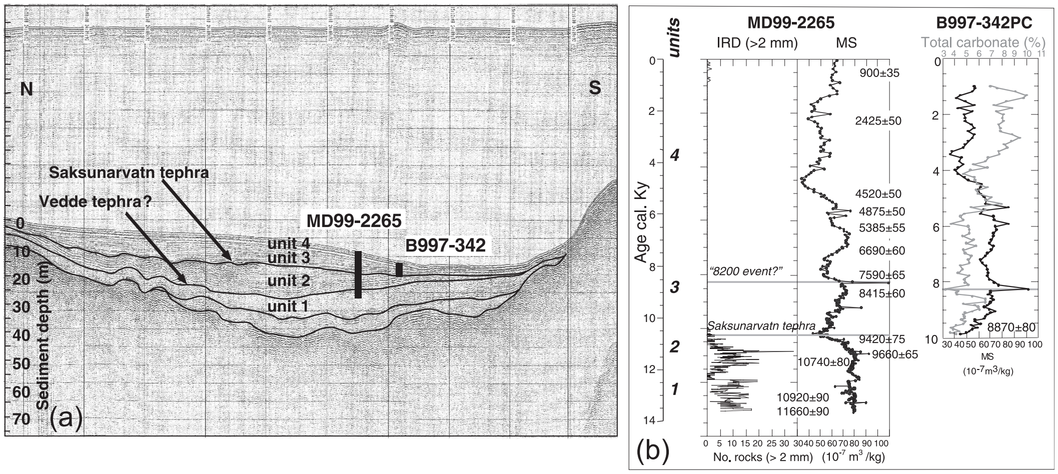


Fig. 3. (a) Seismic profile of Jökulfirdir with core locations (see Fig. 2 for profile locations). Lithofacies units of Fig. 2b are also shown. (b) Magnetic susceptibility, carbonate content and IRD records in the Jökulfirdir cores (MD99-2265 and B997-342). Also shown are lithofacies units for core MD99-2265, the location of Saksunarvatn tephra and the 8.2 cal. Kya event in the core. Available uncorrected ^{14}C dates are projected on the logs.

core causes a decline in MS. Based on the seismic record, ^{14}C dates, tephra layers and a correlation with B997-336, we estimate we lost approximately the top 2 m of this unit (ca. 2 cal. Ky).

B997-338 comprises the diamict and the glacial marine sediment (Fig. 2b). The core was obtained from the side of the trough where turbidites are less likely to be preserved because of marginal currents. The erosional reflectors detected in unit 4 of MD99-2264 mark the top of B997-338, explaining the lack of Vedde tephra in that core. B997-336 comprises the Djúpáll record's uppermost 12 cal. Ky and shows much higher resolution data than an equivalent part of MD99-2264. Its basal part correlates with the erosional reflectors of unit 4 but contains the Vedde tephra (Fig. 2b). The most noticeable feature in B997-336 is a steady increase in carbonate after the deposition of the Saksunarvatn tephra. The value peaks at about 2.5 cal. Kya; thereafter values decrease, probably reflecting diminishing productivity. During the period of increased carbonate there is, however, a pronounced minimum at around 8 cal. Kya, a possible manifestation of the most pronounced Holocene cooling event recognized around the North Atlantic (Alley et al. 1997).

Jökulfirdir—B997-342 and MD99-2265

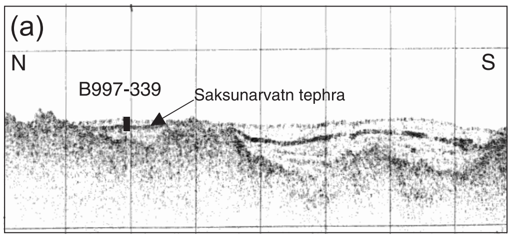
The cores from Jökulfirdir are located between two transverse ridges of morainic origin (Fig. 1). The longer core penetrated two major seismic reflectors at 11 m and 16.2 m, coinciding with the Saksunarvatn tephra and differences in sedimentary texture, respectively (Fig. 3a). According to our age–depth model, this lower reflector corresponds to the timing of the Vedde tephra formation. The tephra layer has not yet been identified and a chemical study is needed to confirm its existence within MD99-2265.

Combining MS measurements and visual inspection of MD99-2265 suggests a fourfold division of the sediment (Fig. 3), as follows.

Unit 1 (13 - 12 cal. Kya), the lowermost unit, comprises silty clay loaded with pebbles, which we believe reflects a glacial marine sedimentation.

Unit 2 (12 - 10 cal. Kya) is mostly silty clay with faint laminations, differing from the basal unit by fluctuating MS. IRD is still abundant; the value peaks around 11 cal. Kya and decreases thereafter. The MS drops abruptly towards the top of the unit, coinciding with the Saksunarvatn tephra in the core. The unit describes an ice-proximal situation, although declining MS and diminishing IRD towards the top suggest a transition from a glaciated to an unglaciated fjord system.

Unit 3 (10 - 7 cal. Kya) also comprises silty clay with faint laminations, but no IRD was counted. The number of shell fragments increases considerably up-unit. MS values rise steadily; they peak about 8 cal. Kya and then decrease at 8 - 7 cal. Kya. Core B997-342 penetrates this unit and



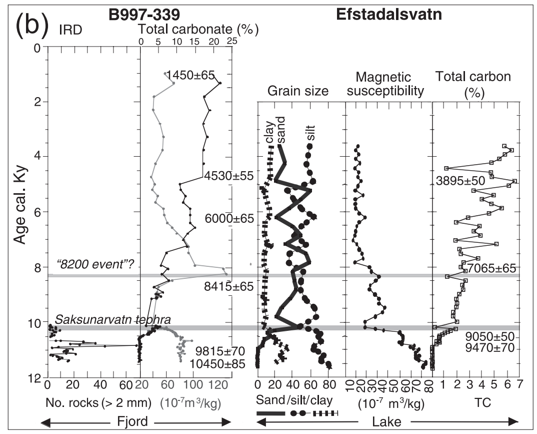


Fig. 4. (a) Seismic profile from Skötufjördur in Ísafjarðjúp with core location (see Fig. 2). Core B997-339 is 527 cm long with a basal date of 11.4 cal. Kya. The strong seismic reflector is at 170 cm in the core. (b) Magnetic susceptibility, carbonate content and IRD records in cores B997-339 and Efstadalsvatn. Also shown are the location of Saksunarvatn tephra and the 8.2 cal. Kya event. Available uncorrected ^{14}C dates are projected on the logs.

shows a near identical MS record. The carbonate record available from B997-342 shows a major low around 8 cal. Kya, similar to that detected in B997-336 from Djúpáll, suggesting a short period of increased terrigenous input into the fjord system and/or less bioactivity in the sediment.

Unit 4 (7 - 0 cal. Kya), the uppermost unit, comprises well bioturbated silty clay with numerous shell fragments. Changes in MS are related to local changes in the margin of Drangajökull and meltwater discharge into the fjord. MS values drop to a minimum around 4 cal. Kya and stay relatively stable after that. The carbonate low at 3 - 1 cal. Kya may indicate the effect of neoglaciation in the fjord. Some IRD is detected in the uppermost 0.8 cal. Ky.

Skötufjördur—B997-339—Efstadalsvatn

The seismic profile from Skötufjördur shows one prominent seismic reflector correlated with the Saksunarvatn tephra (Fig. 4a). B997-339 is mostly massive, sandy silt, completely devoid of carbonate until 10.5 cal. Kya, when it ramps up steadily although halted by the deposition of the Saksunarvatn tephra (Fig. 4b). Abundant IRD is found in the core until 10 cal. Kya.

The basal unit of Efstadalsvatn (12 - 11 cal. Kya) is very finely laminated grey silt and clay with high, but decreasing, mass MS but no TC (Fig. 4b). The lake basin was deglaciated just before the formation of this lowermost unit, but the nearness of the glacier is seen in the accumulation of the finely laminated sediment and high MS. At this time a glacier is calving and producing icebergs over site B997-339. Bioactivity starts in the lake around 11 cal. Kya, as seen in the abrupt change in TC%. The prominent lows in TC% at 10.2 and 8.2 cal. Kya in both records are related to the deposition of the Saksunarvatn tephra and more terrigenous influence, respectively. The fluctuating MS and TC% in the uppermost unit of the lake core (8.0 - 3.5 cal. Kya) is best explained by soil instability or differences in erosional patterns around the lake (Caseldine et al. in press).

Glacier retreat from shelf to land

The shelf record comprises the last 36 cal. Ky whereas the oldest fjord record contains ca. 13 cal. Ky. Both successions indicate an increasingly ice-distal depositional setting. Figure 5 shows four time-slices of the VP glacier retreat based on the IRD record and inferred moraines within the Djúpáll–Ísafjardardjúp system.

36 - 15 cal. Kya

The basal diamict in both shelf cores reflects an ice-proximal setting, probably within a few kilometres of the ice margin. This marks the furthest extent of the VP ice cap during the last 36 cal. Ky, although the overlying turbidites indicate an increasing distance from the ice margin (Fig. 5a). The IRD record between 30 and 15 cal. Kya suggests free iceberg drift across Djúpáll during most of that interval. However, the lack of IRD in B997-338 between ca. 21 and 22 cal. Kya coincides with the inferred timing of the LGM (e.g. Ingólfsson & Norddahl 2001) and may be related to shore-fast sea ice conditions (Dowdeswell et al. 2000; Vor-

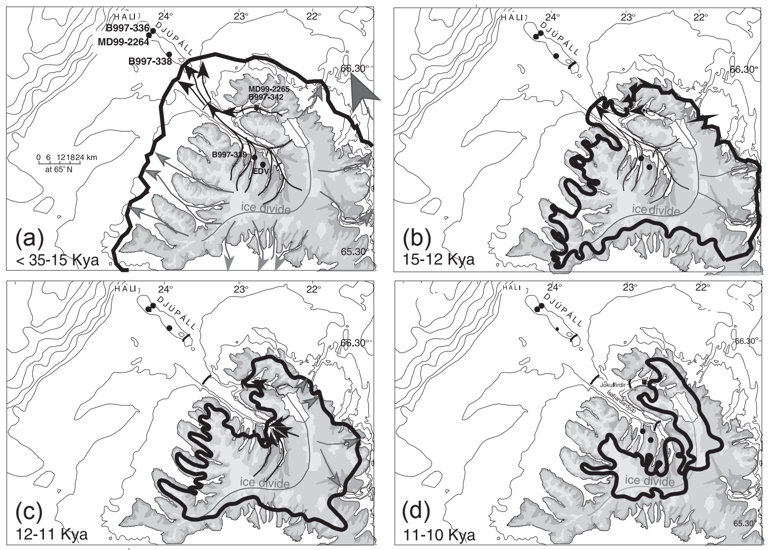


Fig. 5. A series of maps of north-west Iceland showing possible ice margins at different time slices. Black arrows are based on this study, grey arrows are inferred iceflows during different time intervals. A big arrow east of the Vestfirdir peninsula indicates the ice flow from the main glacier flowing out Húnaflói.

ren et al. 1984). This would impede the drift of icebergs and sediments would be predominantly fine-grained and even-laminated, as in B997-338.

15 - 12 cal. Kya

Accumulating data from the west Iceland shelf (Syvitski et al. 1999; Jennings et al. 2000) combined with new data from western Iceland (Ingólfsson & Norddahl 2001) suggest that an ice sheet was grounded close to the shelf edge, 100 - 150 km off the present coast, around 15 cal. Kya. Responding to rapidly rising global sea level, it retreated very fast and had disappeared from the shelf at ca. 14.6 cal. Kya. Our record from the VP shelf shows some IRD around 15 cal. Kya but much diminished after that, which may be related to a similarly hasty retreat of the VP ice cap at that time.

Reestablished turbidity flows and small IRD peaks characterize the shelf cores at 12 cal. Kya. Coinciding with the Younger Dryas chronozone, this may reflect changes in bottom currents, perhaps promoted by sea level fluctuations or distal ice-marginal oscillations and iceberg production (see Lønne 1995). This could also explain the multiple erosional reflectors in the chirp profile. The fjord record reaches back only 12 - 13 cal. Ky, starting with glacial diamict. At this time the inlet fjords may have been more or less filled with outlet glaciers from the VP ice cap that coalesced into the main Ísafjardardjúp (Fig. 5b).

12 - 11 cal. Kya

Numerous IRDs are found in the shelf / fjord record at 12 - 11 cal. Kya, suggesting an actively calving glacier margin (Fig. 5c). However, this interval describes the deglaciation and ice retreat from Ísafjardardjúp to land. That sedimentation had already started in the lake basin of Efstadalsvatn at 11 cal. Kya, when active ice rafting is indicated at site B997-339, is explained by an outlet glacier flowing the shortest distance to the fjord from an ice divide in the south. Glacier activities in the fjords at this time are correlated with the Preboreal glacier advance seen in records from elsewhere in Iceland (e.g. Norddahl 1991; Geirsdóttir et al. 2000).

< 11 cal. yrs

A comparison can be made between the shelf (B997-336) and the fjord / land record for the early Holocene based on the MS and carbonate record. No IRD is detected within the shelf after 11 cal. Kya, while numerous IRDs are found in the fjords until 10 cal. Kya. Finding the Saksunarvatn tephra in our records at 10.2 cal. Kya suggests an ice-free area at all our study sites at that time. We envisage a much reduced ice cap covering only the highlands of the VP and maybe calving into the innermost parts of Ísafjardardjúp and Jökulfirdir, as shown in Fig. 5d.

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