Invited address

Late Quaternary ice extent and glacial history from the Djúpáll trough, off Vestfirdir peninsula, north-west Iceland: a stacked 36 cal. Ky environmental record

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Djúpáll is a ~90 km long by 15 km wide trough which extends from Ísafjardardjúp to the shelf break above Blosseville Basin, north of the Denmark Strait. We present 3.5 kHz seismic profiles from this trough and data from cores collected in 1996 (JM96-1232 and -1234) and five cores collected on cruise B997. We pay particular attention to B997-338 as this core recovered sediments ranging in age between 12 and 36 cal. Ky BP. This is the first such record from the Iceland continental shelf. Dating control is provided by AMS ^{14}C dates and the occurrence of the Saksunarvatn tephra. X-radiographs of the cores enable us to quantify the input of iceberg-rafted detritus (IRD) and to describe the lithofacies. The sediment matrix is fine-grained and might represent either rain-out of suspended sediment plumes or distal turbidites. IRD is present from ca. 12 cal. Ky BP throughout the next 24 cal. Ky with some IRD-free intervals. Using sediment magnetic properties, sampled at 1 cm (~100 yrs/sample) resolution, we provide a stacked environmental record which includes marine isotope stages 1, 2 and part of 3. The sediment magnetic properties kARM and IRM(60), and carbonate and TOC, show multi-millennia quasi-periodic cycles, but there are no obvious events coeval with the North Atlantic Heinrich events. Our data indicate that at the Last Glacial Maximum on the Vestfirdir peninsula (VP), north-west Iceland, ice did not reach the shelf break, but was probably grounded near the mouth of Ísafjardardjúp. A rapid increase in the rate of sediment accumulation suggests that deglaciation of the VP occurred mainly between 11 and 15 cal. Ky BP.

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The purpose of our paper is to document changes in sediment parameters from a stacked series of marine sediment cores that cover the interval 0 - 36 cal. Ky BP from Iceland's north-western continental shelf, specifically Djúpáll, a trough extending seaward from Ísafjardardjúp to the shelf break above Blosseville Basin (Fig. 1). This is the first time the presence of in situ sediments older than 13 Ky BP on the Iceland shelf has been demonstrated. Our study adds

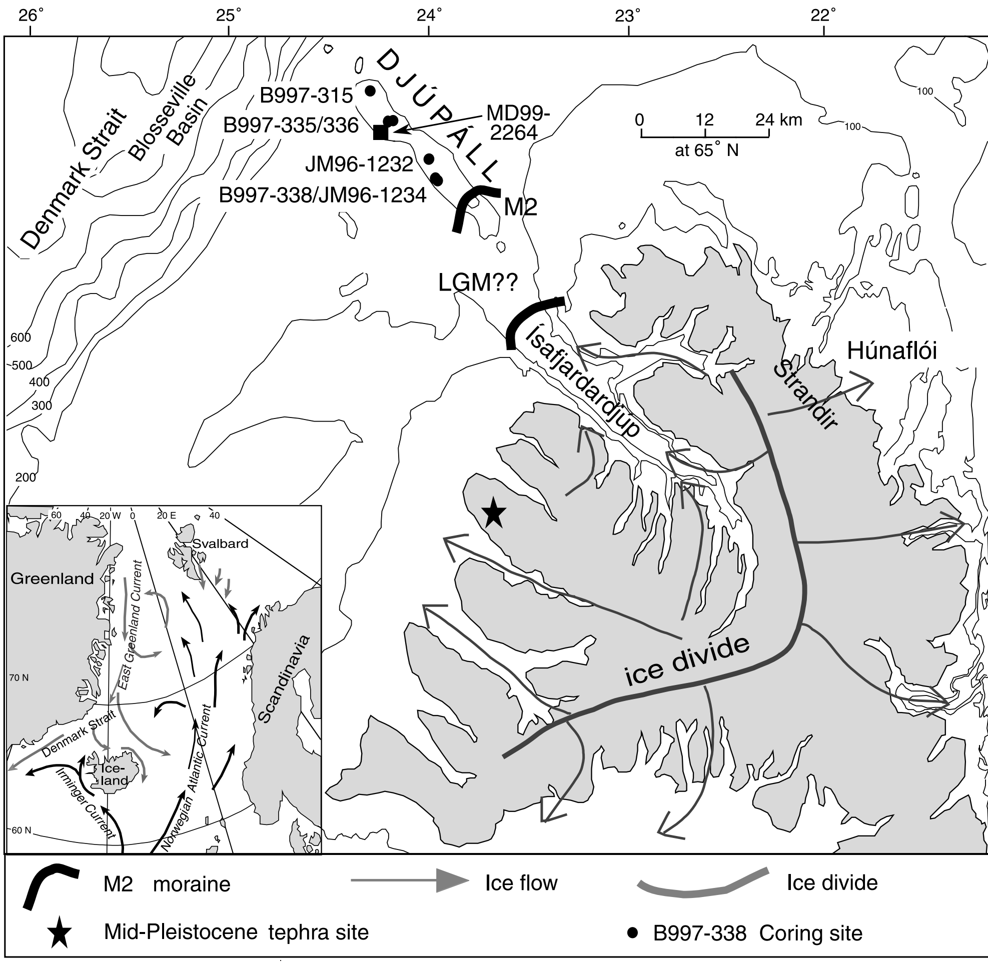


Fig. 1. Location of Iceland (inset) and the inferred ice flow off the Vestfirdir peninsula, north-west Iceland (Norddahl 1990; Bourgois et al. 2000). The 200 m contour defines the Djúpáll trough. Core locations are shown (see Fig. 2 for more detail). The two thick black lines represent moraines; either might be the Last Glacial Maximum ice limit.

vital information to the debate about the Late glacial extent of ice on Iceland's Vestfirdir peninsula (VP) (Norddahl 1991; Rundgren & Ingólfsson 1999; Roberts et al. 2000). Thus, this is the first data set to extend the history of deposition back beyond ca. 12 - 16 Ky BP, when deglaciation resulted in rapid ice retreat from the south-western and north–central coasts (Ingólfsson 1988; Andrews et al. 2000; Eiríksson et al. 2000; Geirsdóttir et al. 2000; Jennings et al. 2000; Ingólfsson & Norddahl 2001).

The cores were obtained on two cruises, one in 1996 on the RV *Jan Mayen* (JM96-, a joint Norwegian–USA cruise), and the others in 1997 as part of an Icelandic / USA cruise on the *Bjarni Saemundsson* (B997) (Helgadóttir 1997). We discuss: 1) the various ideas about the extent of ice and the glacial history of north-west and western Iceland; 2) illustrate the major Quaternary seismic stratigraphic units in Djúpáll; 3) relate the available cores to the seismic stratigraphy and present the accelerator mass spectrometry (AMS) ^{14}C data in support of continuous sediment accumulation in the trough; and 4) outline the changes in depositional regime, as mainly exemplified by sediment and sediment magnetic data.

In this paper, "Ky BP" refers to radiocarbon dates, "cal. Ky BP" refers to calibrated dates, and "Ky" refers to rates or an interval of time.

Review: ice extent and deglaciation, north-west Iceland

Most of north-west Iceland consists of 12 - 16 My old Tertiary basalts with relatively thin interbedded sedimentary units. Numerous fjords have been eroded into the basalt plateau, the largest being the fjord system Ísafjardardjúp (Fig. 1). The sediment deposited in Djúpáll is probably all derived from glacial and fluvial erosion of north-west Iceland, in addition to reworking of shelf sediments from the surrounding shallow banks (Thors 1974).

Glaciological models, coupled to orbital insolation variations, suggest that during the Last Glacial Maximum (LGM) the Iceland Ice Sheet (IIS) formed a single cohesive ice mass which extended to the shelf break all around Iceland (Webb et al. 1999). Glacial geological / geomorphic reconstructions (Bourgeois et al. 2000; Ingólfsson & Norddahl 2001; Stokes & Clark 2001) show major ice streams flowing seaward toward the shelf break, but there is no chronology in such reconstructions, and no specific horizontal limit of glaciation is shown. Bourgeois et al. (2000) and Ingólfsson & Norddahl (2001) both show the VP as a separate ice centre with an ice divide forming a broad U-shape with ice being focused into Ísafjardardjúp (Fig. 1). Information in support of limited ice extent on the VP comes from the low marine limits at the north-west tip of the peninsula, as well as along the Strandir coast and around Húnaflói (Fig. 1) (Hjort et al. 1985; Norddahl 1991; Rundgren et al. 1997; Principato 2000), which implies a relative small ice load (see Sigmundsson 1991). Furthermore the preservation of a Mid-Pleistocene tephra unit (Fig. 1) (Sigurvinsson 1983; Roberts et al. 2000) in lake sediments just south of Isafjardardjúp also implies a restricted ice cover (or preservation under cold-based ice).

The history of the IIS during Marine Oxygen Isotope Stages (OS) 3 and 4 (between ca. 70 and 28 cal. Ky BP) is poorly known. There is evidence for an interstadial event on south-west Iceland during OS 3 (Kristjánsson & Gudmundsson 1980; Eiríksson et al. 1997), which suggests that the ice cap had retreated onto land 30 - 40 Ky BP; it would be reasonable to expect a similar response around the other margins. However, radiocarbon dates in this range are lacking, although foraminifera in diamictons have given ages in this range from glacial marine sediments in Húnaflóaáll (Principato 2000; Andrews & Helgadóttir in press). It is generally assumed that the IIS expanded during OS 2 to the shelf break, but direct evidence for this is lacking.

Knowledge of the ice sheet's retreat during the last deglaciation has increased substantially as research cruises have collected numerous sediment cores from the shelf. Late glacial and Holocene marine sediments have been dated and studied around south-west Iceland (Helgadóttir 1984; Syvitski et al. 1999; Jennings et al. 2000), and north Iceland (Kristjánsdóttir 1999; Andrews et al. 2000; Eiríksson et al. 2000). These studies indicate a rapid deglaciation of the shelf during the Bølling–Allerød interval (ca. 11 - 13 Ky BP) (Ingólfsson & Norddahl 2001; Andrews in press). Evidence has been presented (Rundgren 1995; Eiríksson et al. 2000; Jennings et al. 2000) for colder conditions during the Younger Dryas, although the extent of ice on the VP during the Younger Dryas is unclear (but see Geirsdóttir et al. 2002).

Bathymetry and oceanography

Djúpáll cuts across the north-west Iceland shelf and appears as a direct continuation of Ísafjardardjúp (Figs. 1, 2b). The trough is around 90 km in length and averages 10 - 15 km in width. The maximum depth is close to 240 m. Above the trough, the shelf is relatively wide with depths in the range of 140 - 200 m. The profile along the trough is generally smooth but with a vertical relief of 10 - 20 m in places. The depth at the break overlooking Blosseville Basin is 200 m (Fig. 1). Between the Djúpáll trough and Ísafjardardjúp there is a small sill as the depth decreases to 100 - 120 m just outside the fjord (Fig. 2).

The north-west shelf of Iceland is presently bathed in Atlantic Water which is transported northward in the Irminger Current (Hopkins 1991). The outer part of the shelf is, however, close to the Polar Front, where the Atlantic Water contacts Polar Water moving southward in the East Greenland Current.

Methods

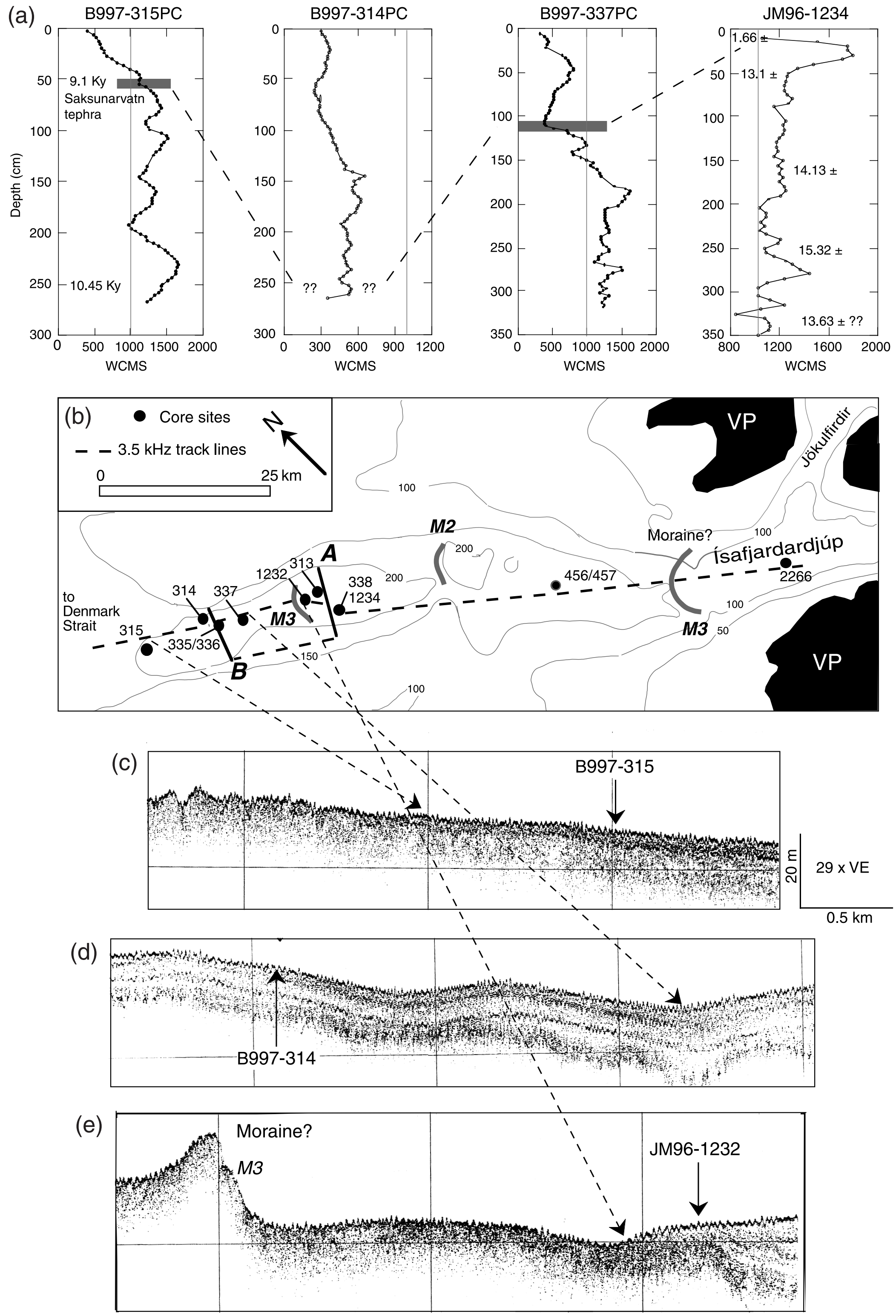
Analog acoustic 3.5 kHz profiles were obtained in 1996 and 1997 and supplemented earlier seismic surveys conducted by the Marine Research

Institute (Thors & Helgadóttir 1999). In 1996 the survey ran from the sediment fill in the southern part of the Blosseville Basin (cores JM96-1228 and -1229; Hagen 1999; Cartee-Schoolfield 2000), up the slope and then along the long axis of the trough. The B997 acoustic survey lines (Helgadóttir 1997) "boxed" the trough with two cross-sections (Fig. 2b). Cores were taken at sites based on the seismic stratigraphy and were either 10 cm diameter gravity cores (JM96-) or 7 cm diameter piston cores (B997). Upon retrieval the JM96 cores were cut into 1 m lengths, whereas the B997 material was divided into 1.5 m sections. The volume magnetic susceptibility of the cores (Table 1) was measured on the whole cores using a Bartington MS2 meter (Fig. 2a). The individual core sections were subsequently sampled using a 2×2 cm u-channel. The palaeo-magnetic and sediment magnetic measurements of the u-channels were carried out at the Paleomagnetism Laboratory at University of California, Davis, using a 2G Enterprises Model 755R long-core magnetometer. The u-channels were measured at 1 cm intervals; however, the response function of the magnetometer pickup coils will smooth the data slightly. In addition to natural remanence magnetization (NRM) and volume susceptibility (MS), anhysteretic remanence magnetization

Fig. 2 (opposite page). (a) Selected logs of whole core magnetic susceptibility. (b) The bathymetry of the north-west Iceland shelf and core locations (2266 is a 40 m long IMAGES core obtained in 1999), and 3.5 kHz seismic sections. The letters A and B on Fig. 2b locate cross-sections a-1 and b-1 on Fig. 3. (c) 3.5 kHz profile on the outer shelf. (d) Profile along the trough showing the presence of internal reflectors; the upper one is the Saksunarvatn tephra. (e) Long profile along the trough in the vicinity of moraine (?) M1.

Table 1. Core locations and radiocarbon dates used in this paper. Calibrated ages were calculated using the Calib 4.0 radiocarbon program (Stuiver & Reimer 1993) and applying a modelled ocean reservoir correction with the addition of a constant ±100 year error. In core 338, ages older than 22 Ky were calibrated by adding a 2000 year correction.

Depth (cm)	Date (^{14}C yrs BP)	Error	Calibrated age BP	Error range	Lab. number
JM96-1232GGC (66° 37.02'N, 24° 0.0'W; 215 m water depth; 279 cm long)					
1	2805	60	2540	2345 - 2715	AAR-3708
101	5590	65	5945	5870 - 6153	AAR-3709
199	8360	80	8885	8745 - 8965	AAR-3710
280	9060	70	9784	9465 - 9838	AAR-3515
JM96-1234GGC (66° 35.25'N, 23° 58'W; 223 m water depth; 365 long)					
1	2060	50	1618	1505 - 1770	CAMS-46524
55	13 460	70	15 585	15 360 - 15 845	CAMS-46525
159	14 530	90	16 824	16 550 - 17 110	CAMS-46526
259	15 720	70	18 195	17 895 - 18 505	CAMS-46527
349	14 030	70	16 250	15 990 - 16 515	CAMS-50405
B997-335PC (66° 41.207'N, 24° 10.698'W; 239 m water depth; 427 cm long)					
1	1800	200	1330	1140 - 1575	AA-31263
169	9490	70	10 273	9875 - 9925, 9995 - 10 310	AA-29195
182	~9000		10 180 ± 60	Saksunarvatn ash	—
428	10 350	80	11 185, 11 255, 11 185	11 085 - 11 410, 11 460 - 11 625	AA-27760
B997-336PC3 (66° 41.2'N, 24° 09.7'W; 242 m water depth; 501 cm long)					
1	1965	60	1520	1380 - 1670	AA-31364
143	9240	200	9835	9600 - 10 275	AA-31266
143	~9000		10 180 ± 60	Saksunarvatn ash	—
379	10 705	80	11 755, 11 810, 11 935	11 500 - 12 315	AA-31267
454	10 860	160	12 185, 12 205, 12 320	11 720 - 12 805	NSRL-10776
485	13 385	90	15 520	15 265 - 15 765	AA-32967
501	13 680	70	15 845	15 585 - 16 105	CAMS-42013
B997-338PC (66° 35.3'N, 23° 58.6'W; 209 m water depth; 412 cm long)					
21	11 560	170	13 020, 13 105, 13 115	12 895 - 13 175	AA-34406
99	19 280	420	22 290	21 690 - 22 905	AA-34407
319	31 900	1700	? 33 900	?	AA-34408
412	34 600	640	? 36 600	?	AA-32968



(a)
B997-315PC
B997-314PC
B997-337PC
JM96-1234
Depth (cm)
WCMS
9.1 Ky
Saksunarvatn
tephra
10.45 Ky
??
1.66 ±
13.1 ±
14.13 ±
15.32 ±
13.63 ± ??
(b)
Core sites
3.5 kHz track lines
N
0
25 km
VP
Jökulfirdir
Moraine?
Ísafjardardjúp
M2
M3
A
B
to
Denmark
Strait
315
314
337
335/336
1232
313
338
1234
456/457
2266
(c)
B997-315
20 m
29 x VE
0.5 km
(d)
B997-314
(e)
Moraine?
M3
JM96-1232

(ARM at 100 mT AF field and 0.5 mT DC field) and isothermal remanence magnetization (IRM at 1T) were measured on the u-channels. Stepwise demagnetization was imparted to the u-channel at levels assigned by running pilot samples from similar sediment types.

Discrete samples were obtained from all cores at every 5 cm for magnetic, sedimentological and chemical analysis. The mass susceptibility (massMS × 10-7m3/kg) of discrete samples was measured. It is particularly useful to compare the carbon values with the magnetic results as in addition to being a reasonable indicator of productivity, carbon can greatly affect magnetic results by diluting the magnetic signal. Thus, both total carbon (TC) and total inorganic carbon (TIC) were measured in all cores using a UIC CM5012 CO2 Coulometer (Andrews et al. 2002). The percentage of total organic carbon (TOC) was obtained by subtracting TIC values from TC values. The archive half of the 338 core was scanned at 2 cm intervals using the Colortron TM spectrophotometer, which non-subjectively measures and quantifies colour changes in the core (Andrews & Freeman 1996). The output data from the Colortron are reported in the CIE* convention, where L is a measure of brightness (black to white), a* is a measure of redness (+) and greenness (-), and b* measures yellowness (+) to blueness.

Seismic stratigraphy

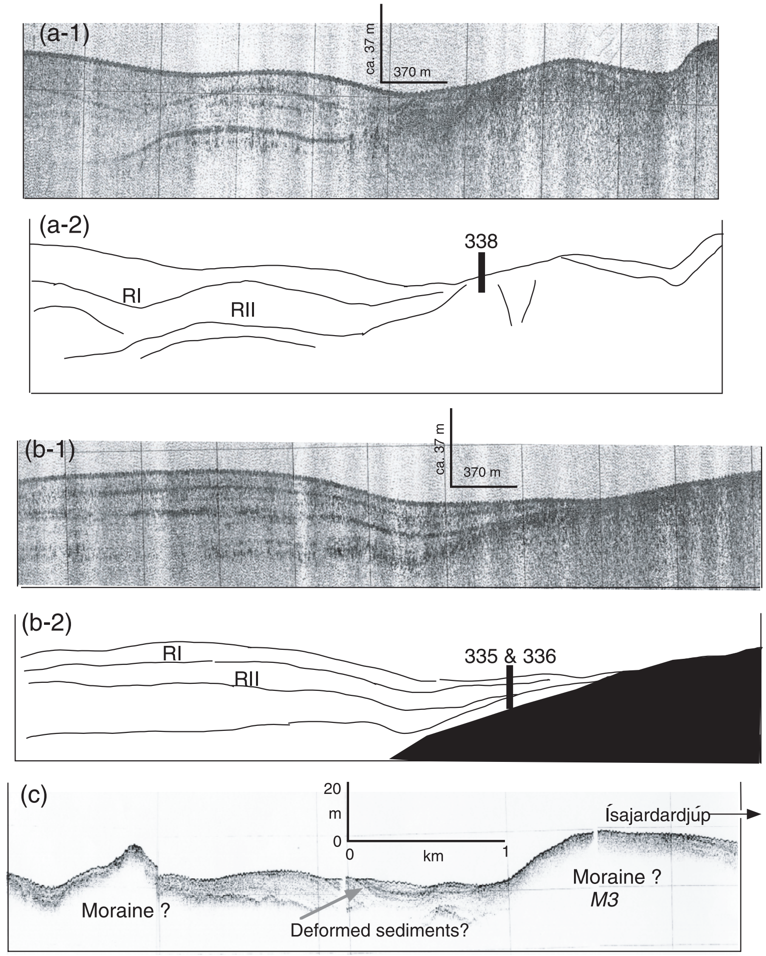
The results of seismic surveys across the area, have been reported by Thors & Helgadóttir (1999). In this paper we present 3.5 kHz data from surveys in 1996 and 1997 (Figs. 2, 3). The line tracks are shown on Fig. 2b, which also indicates the bathymetry and core locations. The sediment thickness in Djúpáll is 10 - 40 m. Sediment is not distributed evenly along the 90 km length, but is concentrated in relatively modest basins separated by areas of bedrock or areas of diamicton with no seismic penetration (Figs. 2c–e, 3). These shelf sediment bodies, or shelf drift deposits (Harris et al. 2001), are thickest in the mid-part of the trough and thin toward the lateral margins (Fig. 3a, b).

At depths < 200 m the outer part of the trough (Fig. 2c) is scored by a series of small troughs and ridges which may represent old iceberg scours (Syvitski et al. 2001). Quaternary sediments onlap the bedrock as a thin wedge (Fig. 2c) which thickens (Fig. 2d) in the vicinity of B997-335/336 (Fig. 3b) but appears not to exceed 30 - 40 m in thickness. A moraine (M1) may divide the > 200 m deep basin into two parts (Fig. 2b, e). Progressing farther toward land there is a series of smaller basins which lie seaward of a large, seismically opaque, ridge (M2) which may represent the LGM terminal moraine (Thors & Helgadóttir 1999) (Fig. 3c). Immediately proximal to the inner ridge on Fig. 3c there is a small basin where the sediments are deformed and then truncated. This might reflect the LGM advance. The flat-topped inner moraine (M3) on Fig. 3c has a similar surface geometry to those described from shallow water conditions in Norway (Lønne 2001), but we cannot see any internal structures in these 3.5 kHz records. Sediments seaward of the outer ridge in Fig. 3c tend to drape over older sediments whereas behind the moraine the sediments of Ísafjardardjúp have little relief and appear ponded behind the moraine.

Both the long and cross-section seismic profiles in Djúpáll (Figs. 2c–e, 3) are characterized by one or two regional reflectors which can be tracked over large distances within the trough (RI and RII; Fig. 3). We have shown that RI represents the accumulation of tephra during the Saksunarvatn 9.0 ± ^{14}C Kya eruption (Andrews et al. in press). The sediments from this event gives a characteristic sediment magnetic signal which consists of a distinct low in both the whole core magnetic susceptibility and massMS. This characteristic can be seen in some of the records presented in Fig. 2a.

The deeper reflector (RII; Fig. 3) may be the subsurface reflection of the 10.3 ^{14}C Kya Vedde tephra. The Vedde ash was present in core 336 at a depth of 450 cm. A beautiful high resolution seismic cross-section of Djúpáll (Geirsdóttir et al. 2002, see their Fig. 2) shows greater detail of the complex sediment architecture. There the reflector coincides with a distinct erosional surface which correlates with the Younger Dryas chronozone. In the seismic cross-sections (Fig. 3a, b), RI and RII are clearly “cut-out” on the margins of the troughs. In 1997 our piston corer had a maximum possible penetration of 6 m; we therefore located several of our key sites on the flanks of the trough to sample the sediments older than RI and RII (Fig. 3). The interpretations of the seismic surveys in terms of depositional environments will become clearer once some

Fig. 3. Cross-sections of the Djúpáll trough (see Fig. 2b for profile locations). (a) Cross-section at site 338 showing (a-1) the 3.5 kHz profile and (a-2) the seismic interpretation. RI and RII indicate the regional reflectors. (b) Cross-section at core sites 335 and 336: (b-1) represents the seismic profile; (b-2) shows the interpretation. (c) Cross-section closer to Ísafjardardjúp. This section extends across the innermost moraine shown on Fig. 2b and extends seaward.



knowledge of the chronology of deposition is established. This we do in the next section.

Core chronology and correlations

From the available cores collected in 1996 and 1997 we focus on the records from B997-336 and -338 (henceforth 336, 338 etc.) and use the information from B997-335, and JM96-1232, and -1234 as supplemental information (Figs. 1, 2a). All dates used in this paper are described in detail in a Radiocarbon Date List (Smith & Licht 2000). The AMS ^{14}C dates (Table 1) were converted to calender years by applying CALIB4.0 (Stuiver & Reimer 1993). We used the modelled ocean reservoir correction ($\Delta R = 0$), but attached a ± 100 year error to this because the correction has varied (Bard et al. 1990, 1994). Particularly in the interval 10 - 12 Ky BP (~11 - 14 cal. Ky BP) the ORC could be much larger (Bard et al. 1994; Voelker et al. 1998; Hagen 1999), and accurate "true" ages are difficult to obtain because of the various ^{14}C plateaus during this period (Ammann & Lotter 1989; Wohlfarth 1996). The CALIB4.0 program does not extend its calibration beyond 22 Kya and the amount of correction required for dates in the 30 - 40 Ky BP range is uncertain (Kitagawa & van der Plicht 1998; Beck et al. 2001). We have added a 2000 year correction to the dates in this age range from B997-338 (Table 1) to accommodate the observed differences between radiocarbon dates and calibrated records. A prominent dark basaltic tephra layer occurs in both 335 and 336 and can be correlated with reflector RI (Figs. 2, 3); this unit is identified as the Saksunarvatn tephra (Andrews et al. in press) which has an age of $10\,180 \pm 60$ cal. yrs BP

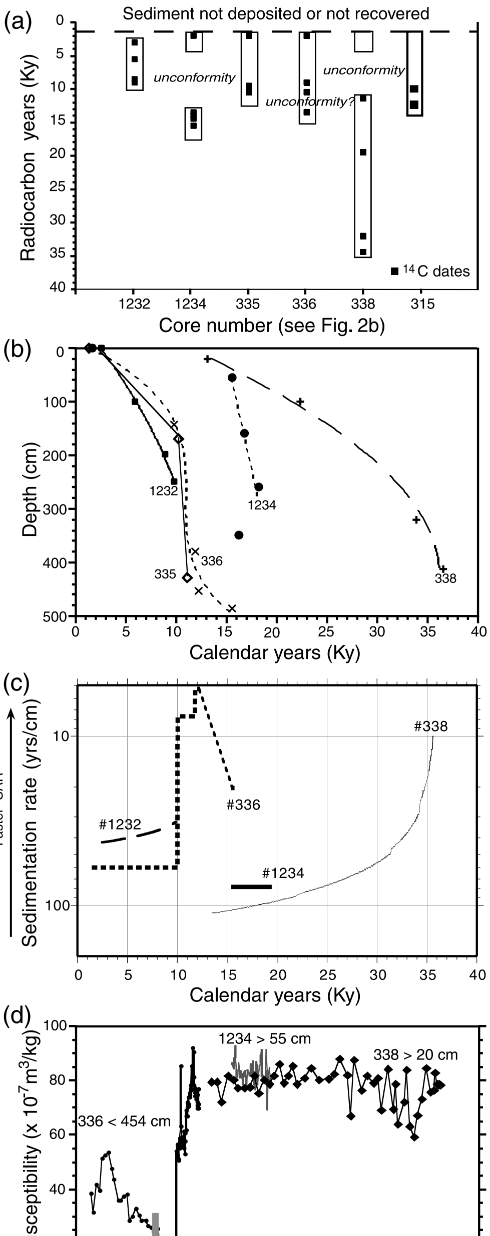


Fig. 4. (a) Temporal coverage of cores in Djúpáll (see Fig. 2 for location). (b) Age–depth relations for five cores (see data in Tables 1 and 3). (c) Sediment accumulation rates (SAR) vs. cal. Ky. (Note the log scale on SAR.) (d) Stacked records from B997-336, -338 and JM96-1234 showing variations in mass magnetic susceptibility over the last ~36 cal. Ky.

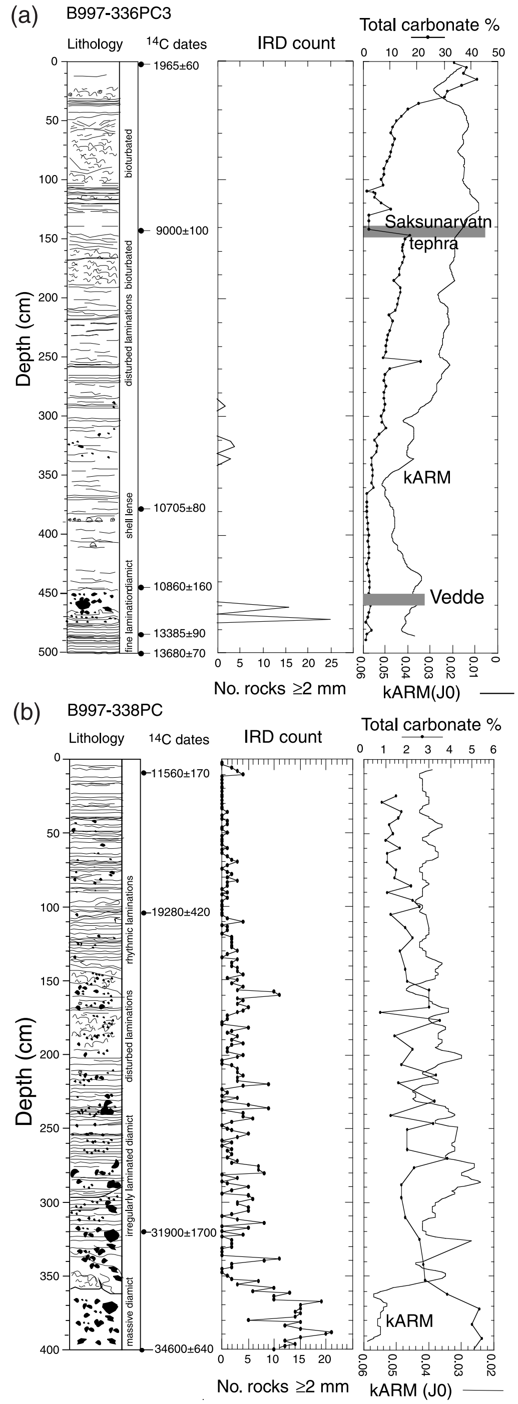


Fig. 5. Lithofacies logs (a) 338 and (b) 336, showing available radiocarbon dates, IRD counts at 2 cm intervals, total carbonate content (weight %) in the sediment, and the ARM susceptibility (kARM).

in the Greenland ice core (Grönvold et al. 1995).

Dates on our core tops invariably give ages ~1.5 Ky BP. Hence, we are either missing the last 1 - 2 Ky of record or there has been no deposition—we favour the first suggestion. Figure 4a shows the temporal coverage of the cores. Only one core (338) extends back beyond 16 Ky BP, whereas three cores (335, 336 and 1232) provide good coverage for the Holocene. There is seismic evidence for depositional hiatuses within Djúpáll, especially within the Holocene (Fig. 3a, b). This is confirmed by the stratigraphy near the tops of 338 and 1234. Furthermore, dates from 336 within 30 cm of each other differ by nearly 3 Ky (Table 1, Fig. 5). Inspection of the sediment and X-radiographs indicate that this interval consists of a tephra-rich turbidite. The geochemistry of the tephra indicates similarities with the Vedde tephra, which has an age estimate of 11 980 ± 80 cal. yrs BP (Grönvold et al. 1995). Our existing coverage is scanty between ca. 12 and 16 cal. Ky BP although we have sections of this interval at the base of 336 and for much of 1234.

Age models for the cores and sediment accumulation rates (SAR)

The statistical data for the age controls on 336, 338 and 1232 are listed on Table 1 and graphed as Fig. 4b. For 336 we only use the depth–age relationships above the date at 454 cm because there is an erosional interval at this depth which is understandable on the basis of the geometry of these "shelf sediment bodies" (Fig. 3b); however, the laminated sediments at the base of 336 with dates of ~13.5 Ky BP (Fig. 5) are considered coeval with similar sediments in 1234 and 338. Because of the rapid rates of sediment accumulation in the lower 2 m of 336, any simple polynomial least-squares regression cannot accommodate the data. For this site we have therefore used three linear regression segments between 0 - 144, 144 - 379, and 379 - 454 cm; we do not calculate a rate for the interval below 454 cm. The ^{14}C dates and the physical and chemical characteristics of cores 335 and 336 are similar. Using the mass magnetic susceptibility data from 336 (versus age) and 335 (versus depth), the correlation between the two records has a value in AnalySeries (Paillard et al. 1996) of $r = 0.966$. This indicates a close correspondence between these two adjacent cores (Fig. 2b). Based on this excellent correlation, we have chosen to use only the longer 336 record in our environmental interpretations. In 338 only the depths ≥20 cm are used because of an erosional unconformity. Although the correlation coefficient for depth–age at site 338 is statistically significant, the errors on the regression coefficients are large because the limited number of points (Andrews et al. 1999). This effect is seen in the size of the root mean square errors.

Figure 4c shows the trends of sedimentation accumulation rates (SAR) in Djúpáll for the last 36 cal. Ky BP. Given the geometry of the sediment body (Fig. 3) we expect both spatial and temporal variations. The SARs were determined from differentiating (Table 2) the linear or polynomial depth–age plots. Different SARs are obtained from interpolation between successive data points, but the intent here is to use depth–age models for the reasons discussed by Andrews et al. (1999). At core 338 the SAR decreases with time and averaged 60 yrs/cm, or 17 cm/Ky; our estimate for 1234 also lies close to that (Fig. 4a). The two dates from below the hiatus in 336 give rates of about 20 yrs/cm, but above this in 336 and in 335 (not shown) the SAR is very high at 5 - 10

Table 2. Regression coefficients and errors on age models for cores B997-338, B9-97-336 and JM96-1232. D = depth in cm, n = number of dates, RMSE = root mean square error.

B997-338
$\text{Age} > 11\,000 = 11\,194 \pm 1489 + 117.25 \pm 21.4 * D - 0.1372 \pm 0.049 * D^2$
$r = 0.998$, $n = 4$, RMSE = 1274
B997-336 (three linear segments)
Age (0 - 144 cm) = 1459 + 59.57*D
Age (144 - 379 cm) = 8908 + 7.65*D
Age (379 - 454 cm) = 9813 + 5.27*D
JM96-1232
$\text{Age} < 11\,000 = 2430 \pm 333 + 42.7 \pm 5.7 * D - 0.057 \pm 0.019 * D^2$
$r = 0.999$, $n = 4$, RMSE = 336

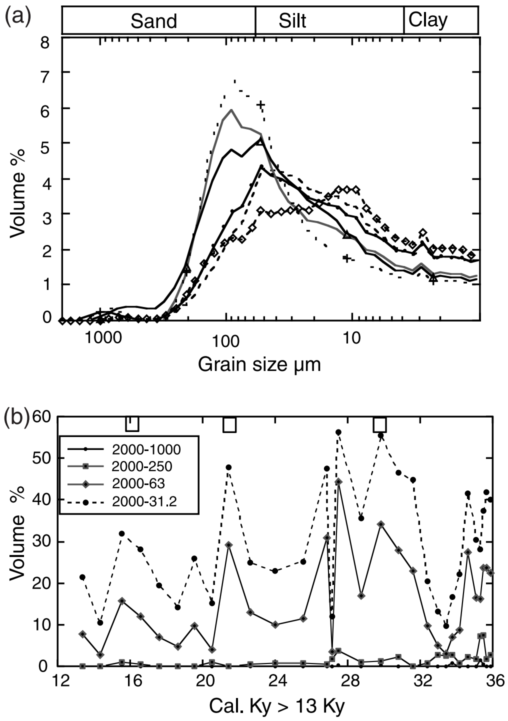


Fig. 6. (a) Grain size spectra of samples from B997-338; the inset box lists depths and estimated ages. The distribution is truncated at 1 µm. (b) Downcore plots of the different size fractions (see insert box). The location of Heinrich events 1, 2 and 3 are shown as black boxes (although we are aware of the problem of assigning ages due to the uncertainty of the ocean reservoir correction).

yrs/cm. This peak of sediment accumulation then declines rapidly, and the rate over the last 10 cal. Ky BP lies close to that of 1232 at 70 - 80 yrs/cm. The rapid influx of sediment during the Bølling–Allerød––Younger Dryas interval mirrors the data from JM96-1229 north of the Denmark Strait sill and below Djúpáll (Cartee-Schoolfield 2000), dates on deglaciation on the north Iceland shelf (Andrews in press), and deglaciation of Jökuldjúp off south-west Iceland (Jennings et al. 2000). We expect high rates of sediment accumulation to track deglaciation, the so-called interval of paraglaciation (Church & Ryder 1972). Hence we infer that significant deglaciation of the VP did not occur until quite late in the deglacial cycle, apparently 1 - 2 cal. Ky after the Heinrich-1 event (16 cal. Ky BP) and the onset of significant deglaciation around the Nordic seas (van Kreveld et al. 2000).

Lithofacies and IRD records

X-radiographs were obtained on all cores, which together with visual descriptions, have been used to describe the lithofacies changes in cores 336 and 338 (Fig. 5); these two cores span the last 36 cal. Ky. We used the X-radiographs to count the number of clasts >2 mm (Grobe 1987; Andrews et al. 1998). Some of these clasts might be pumice fragments but ongoing inspection of the sand fraction indicates that such particles are not common. We also show on Fig. 5 the downcore variations in the carbonate content and the ARM susceptibility (kARM) for both cores (Walden 1999).

Core 338 is predominantly fine-grained, with IRD clasts “floating” in the matrix. The sediments show variations in the degree of lamination and angles of inclination (Harris et al. 2001). Few, if any, units could be visibly identified as graded. The number of IRD clasts fluctuate considerably and could either represent essentially a random depositional system or one more influenced by changes in climate. A coarse diamicton occurs at the base of the core. Core 336 consists mainly of laminated sediments or bioturbated sediments. There is coarse diamicton at 450 cm above a fine-grained laminated interval. Overall the most noticeable change in sediment characteristics between 338 and 336 (glacial to non-glacial) is the reduction in IRD and the increase in carbonate content. The former (Fig. 5) suggests that there was no significant ice-free interval on the VP between ~11 and 36 cal. Ky BP. The most notable feature of these cores is the dominance of laminated sediments. Ó Cofaigh & Dowdeswell (2001) identified a number of processes which could produce fine-grained laminated glacial marine sediments, including suspension settling, contour currents, and distal turbidity currents. If a large ice stream occupied Ísafjardardjúp during OS 3 and 2 then a possible depositional analog might exist in the area of East Greenland, in either Scoresby Sund (Ó Cofaigh et al. 2001) or Kangerlussuaq fjord / trough (Smith & Andrews 2000). A difference between our cored records and those noted above is that we see little evidence for debris flows (Fig. 5).

Grain size spectra were derived for 30 samples using the Malvern laser sizer (Andrews et al. 2002) (Fig. 6). The majority of the samples are silty sands with a mode at 100 µm, but some sediments are finer with modes at 10 µm (Fig. 6a). These spectra differ markedly from glacial-marine/subglacial diamictons that we recovered from the Húnaflói area (Fig. 1) (Andrews & Principato in press) which have strong modes near 10 µm and a secondary peak in the 2000 to 200 µm range. A downcore plot of the different size fractions (Fig. 6b) indicates that the sediments in 338 have limited percentages between 2000 and 250 µm and between 10 and 55 % of the sediment is in the fine sand to medium-silt size range. On Fig. 6b we place the temporal location of Heinrich (H) events 1, 2 and 3 (Elliott et al. 1998). There appears to be some correlation between the peaks in the 2000 - 63 µm fraction and North Atlantic H events, but we are reluctant to comment further because of the limited chronological control.

On the East Greenland margin (Jennings & Weiner 1996; Dowdeswell et al. 2000) the variations between fine-grained, largely IRD-free sediments and matrix supported diamictons have been ascribed to changes in the extent and duration of sea ice. In their model, if a landfast sea ice sheet extended across the trough, this would impede the drift of icebergs and sediments would be predominantly fine-grained. The irregular presence of IRD throughout the interval covered by 338 indicates that icebergs were able to drift across the site, although we detect an interval between 21 and 22 Ky BP (LGM?) with virtually no IRD. Work on provenance is required to ascertain whether the clasts are predominantly from the 12 - 16 My old outcrop on the VP or contain foreign materials from further north, most probably from East Greenland.

Sediment properties

We present our data on the sediment in Djúpáll in terms of their lithofacies (see Fig. 5), sediment characteristics (Figs. 6, 7) and sediment magnetic variations (Fig. 8).

Colour

We show the changes in L and a* of core 338 plotted against age in Fig. 7a. On opening the core it was readily evident that this core was rare amongst cores from the Iceland margin (Andrews et al. 2000), as it consisted of marked colour changes, primarily (to the eye) changes in redness. Figure 7a shows rapid oscillations in both colour parameters. What is also noticeable is that the variability of the a* colour index increases markedly between about 28 cal. Kya to the base of the core.

Carbonate and TOC

Figure 7b shows stacked records for carbonate and TOC (see Fig. 5). The Icelandic bedrock is essentially devoid of carbonate and organic carbon, hence, we interpret changes in these variables to largely reflect variations in the net productivity within Djúpáll (Thórdardóttir 1984; Syvitski et al. 1990). Foraminifera probably constitute the bulk of the carbonate in core 338. There is a slight, but persistent, peak in carbonate at the base of the 338 (36 cal. Ky BP), but during the next 24 cal. Ky weight % of carbonate fluctuates slightly, but consistently, between 2 - 3 %, which is well within the measurement error of the Coulometer (Andrews et al. 2002). During this same OS 2/3 interval, TOC averaged about 0.1 %. However, starting at about 12 cal. Ky BP carbonate weight % ramped steadily up to approach 20 % in the interval prior to the deposition of the Saksunarvatn tephra at 10.18 cal. Ky BP. TOC also increased by about a factor of six (Fig. 7b). The sediment associated with the Saksunarvatn tephra interval is largely barren of carbonate. Hence the record shows a carbonate minimum at this time; thereafter, there is a steady increase in carbonate to surprisingly high values for a high latitude trough site, with a peak value of 43 % being reached at approximately 2.5 cal. Ky BP. Thereafter values decreased, probably reflecting a decrease in productivity during the latter part of the Neoglacial. A similar trend has been reported at several sites off northern Iceland (Andrews et al. 2001). During the period of increased carbonate there is, nevertheless, a pronounced minimum at about 8 cal. Ky which may be a manifestation of the North Atlantic 8.2 cal. Kya cold event (Hald & Hagen 1998; Barber et al. 1999).

Sediment magnetism

Changes in sediment magnetism reflect changes in magnetic concentration, magnetic grain size, and magnetic mineralogy, which can in turn be interpreted as changes in environmental conditions (Walden et al. 1992; Walden 1999). There are several striking features of the stacked record for massMS (Fig. 4d). From ca. 36 to 14 cal.

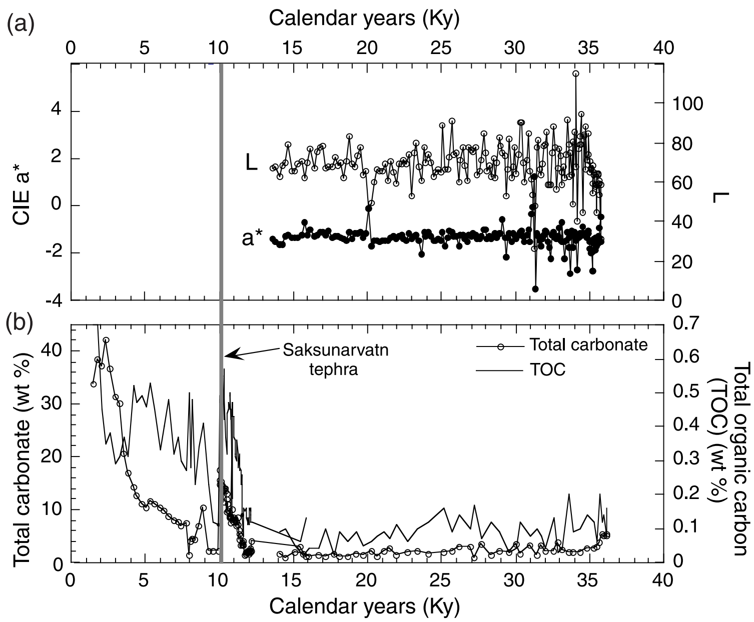


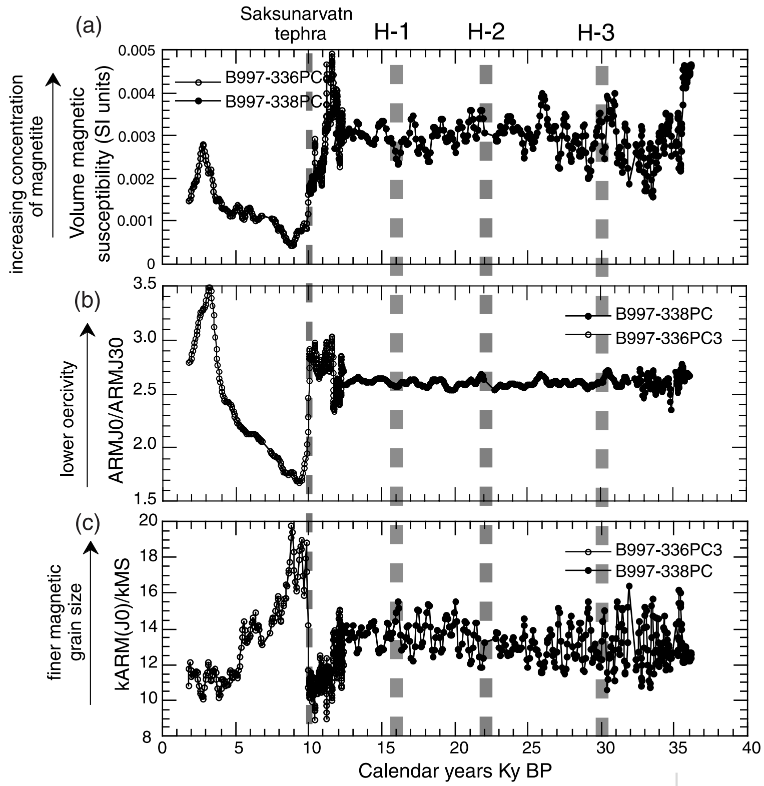
Fig. 7. (a) The colour variables a* and L in core B997-338PC. (b) Total carbonate and TOC records vs. age in cores B997-336PC3 and -338PC.

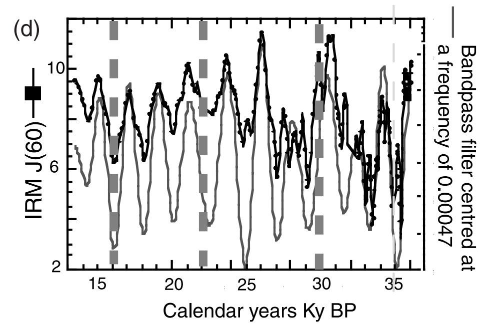
Ky BP the sediments have high massMS (60 to $90 \times 10^{-7} m^3/kg$); this is the interval where we have near continuous IRD in 338—apart from a possible "barren" interval between 21 - 22 cal. Ky BP (Fig. 5). Although we have a limited chronology for 1234, Fig. 4d shows that the massMS of this core falls along the trend for 338 between 16 and 19 cal. Ky BP. High massMS values persist until 11 cal. Ky BP, when they plummet rapidly to between 20 and $50 \times 10^{-7} m^3/kg$. The Holocene shows variability within the range noted above, although none of the cores cover the last 2 Ky. The relatively low massMS intervals estimated to date between 31 and 34 cal. Ky BP (Fig. 4d) coincide with moderate carbonate values indicating that marine organisms were able to exist. In addition, IRD inputs were also limited at this time (Fig. 5). There is no hint in the massMS data for any dramatic increase in this parameter during the LGM as might be expected if the ice cap over the VP expanded and moved down Djúpáll, close to our sites (Figs. 1).

Other magnetic parameters were measured on the u-channels in cores 335, 336, 1232, 1234 and 338 at 1 cm resolution and represent units per volume. As noted above, we elected to present a stacked record of changes in sediment magnetic properties based on cores 336 and 338. Figure 8a–c shows the volume magnetic susceptibility (see also Fig. 2a), ARM(J30)/ARM(J0), and kARM/kMS. There is good agreement between the mass and the volume susceptibility, although the susceptibility peak at 11.5 cal. Ky BP is more pronounced in the volume susceptibility and coincides with an IRD peak. There is less variability in kARM in 336 although there is an overall decrease in this parameter, no doubt in part related to the decrease in wet sediment unit density. The ARMJ0/ARMJ30 record (Fig. 8b) provides a measure of coercivity (Heider et al. 2001), where low values are indicative of higher coercivity minerals (such as hematite). The graph shows a very pronounced change in coercivity at the deposition of the Saksunarvatn tephra layer at 10 cal. Ky BP suggesting a change towards higher coercivity minerals. This might represent a greater amount of oxidized hematite within the Saksunarvatn tephra fall-out than the detrital sediment, but more detailed research is needed to ascertain this.

Figure 8c shows the kARM/kMS parameter which has been interpreted as an indicator of the grain size of the magnetizable material within the sample—termed "magnetic grain size" (King et al. 1982). The magnetic grain size shows great variations within the younger portion of the record, or after 12 cal. Ky BP. A pronounced low in kARM/kMS is seen between 12 and 10 cal. Ky BP, indicating coarser magnetic grain size coeval with deglaciation. Concurrently with the depos-

Fig. 8. Sediment magnetic and palaeomagnetic parameters in cores B997-336PC3 and -338PC from the 1 cm resolution measurements (see text). (a) Volume magnetic susceptibility (compare with Fig. 4d). (b) ARMJ0/ARMJ30, a measure of coercivity. (c) kARMJ0/kMS, an indication of magnetic grain size. (d) The IRM(J60) variations plotted with a bandpass filter (see text). The location of Heinrich events 1, 2 and 3 are shown as black boxes (although we are aware of the problem of assigning ages due to the uncertainty of the ocean reservoir correction).





ition of the Saksunarvatn tephra layer there was a dramatic decrease in magnetic grain size, thereafter there is an increase in this parameter during the Holocene (i.e. kARMJ(0)/kMS decreases; Fig. 8c). Dramatic changes occurred with the deposition of the Saksunarvatn tephra in magnetic concentration, mineralogy and grain size (Fig. 8a–c); thereafter, the mid-Holocene shows a decrease in "hard" coercivity and an increase in magnetic grain size. Some significant changes occurred in the last 2 - 3 cal. Ky but our records did not recover sediments from the interval of the Little Ice Age.

The volume magnetic susceptibility and IRM intensity after demagnetization (J(60); Fig. 8a, d) show evidence of recurring cycles. On Fig. 8d we illustrate this by fitting a bandpass filter (Paillard et al. 1996) centred at a frequency of 0.00047 (periodicity ~2130 yrs) (Fig. 8d). Given the uncertainty in the chronology associated with the size of the ocean reservoir correction we refrain from a detailed discussion although the agreement is quite evident.

Discussion: implications for Late glacial conditions, north-west Iceland

We present the first marine sediment record from the Iceland shelf to span Marine OS 2\ and part of 3. Our work has implications for the Late glacial terrestrial record of glaciation of the VP, and also for the interpretation of North Atlantic deep sea records, which have linked the glacial history of Iceland with both Heinrich and Dansgaard–Oeschger (D–O) events (Bond &

Lotti 1995; Elliott et al. 1998). The fact that the long IMAGES core MD99-2264 from Djúpáll (Fig. 1) (see Geirsdóttir et al. 2002) has a similar chronology, confirms the chronological and stratigraphic implications that we have drawn from core 338. Our data, together with IMAGES core MD99-2264 from Djúpáll (Geirsdóttir et al. 2002), presents the first explicit data in support of a restricted glaciation of the VP during the LGM and thus supports earlier arguments (Hjort et al. 1985; Norddahl 1991). The exact location of the LGM margin is still uncertain, as we do not have sufficient deep core coverage in the critical sections outside of Ísafjardardjúp (Fig. 3c). Our data suggest that the main Djúpáll basin was ice free by ca. 36 cal. Ky BP However, the IRD record (Fig. 5) indicates that the rafting of clasts >2 mm occurred throughout the next 24 cal. Ky suggesting that ice was still present on the VP during the latter part of the Weichselian glaciation, although some sediment may have been contributed from East Greenland as even today icebergs drift into the area.

The coarse diamicton in 336 (Fig. 5) at 450 cm is associated with an uncorrected date of ~10.8 Ky BP (Table 1), represents an interval of ice rafting during the Younger Dryas. Andrews & Helgadóttir (in press) describe a similar facies in cores from of outer Húnaflói (66° 50' N, 20° 13' W) (Fig. 1) also associated temporally with the Younger Dryas. The combined data indicate an interval of active tidewater glacier calving around the VP broadly coeval with the 10 - 11 Ky BP cold event (see Geirsdóttir et al. 2002).

Along this section of the IIS's margin, there are no dramatic changes in the sediments coeval with H events 1, 2, 3 and possibly 4 (Figs. 6, 8). Our chronological control is modest but there are no abrupt changes in IRD, nor sediment magnetic properties, such as we saw in sediments on the East Greenland slope, just across the Denmark Strait, coeval with H events (Andrews et al. 1998). However, the sediment magnetic properties from core 338 show recurring oscillations (Fig. 8d) but at a higher periodicities than H events. Indeed, it is not just the sediment magnetic properties that show significant variability: this also exists in the carbonate and TOC% data (Fig. 7). Peaks in IRM(60) and kARM coincide with peaks in carbonate and TOC. Between 13 and 36 cal. Ky BP the carbonate data suggest recurring periodicities of around 5 and 3 Ky, whereas sediment cores from the Blosseville Basin suggest that the East Greenland Ice Sheet was surging at D–O-like periodicities (~1.5 Ky) (van Kreveld et al. 2000). The covariations between the sediment magnetic properties and measures of marine productivity (Figs. 7, 8) suggests that enhanced open marine conditions varied with harsher conditions during OS 3 and 2. These relationships match the findings from the East Greenland margin where it has been observed that during intervals of decreased sea ice, iceberg rafting increases as do indicators of warmer marine conditions. Conversely, during times of extensive and prolonged sea ice cover, fine-grained laminated sediments are deposited (Jennings & Weiner 1996; Dowdeswell et al. 2000). The presence of inclined and cross-laminated layers suggests that bottom current activity was also an important component in the trough (Harris et al. 2001). Further insights into late Quaternary land–ocean connections off north-west Iceland will be gained by ongoing studies of the foraminifera in cores 338 and MD99-2264, the light isotopic changes of these faunas, and determinations of sediment provenance.

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