Chronology and paleoenvironments during the late Weichselian deglaciation of the southwest Iceland shelf

ANNE JENNINGS, JAMES SYVITSKI, LINDA GERSON, KARL GRÖNVOLD, ÁSLAUG GEIRSDÓTTIR, JÓRUNN HARDARDÓTTIR, JOHN ANDREWS AND SVEINUNG HAGEN

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Foraminifera, sedimentology, and tephra geochemistry in core 93030-006 LCF from the southwestern Iceland shelf were used to reconstruct paleoenvironments between 12.7 and 9.4 ^{14}C ka BP. Seismic-reflection profiles place the core in glacial-marine and marine sediments within one meter of the underlying glacial till. Foraminifers in the earliest glacial-marine sediments provide a record of ice-distal conditions and immigration of slope species onto the shelf in association with warm Atlantic water. Meltwater increased during the Allerød under a weakened Atlantic water influence. Arctic conditions began by 11.14 ^{14}C ka BP with an abrupt increase in meltwater and near exclusion of boreal fauna from the shelf. Meltwater diminished in the early Younger Dryas, coinciding with sea-surface cooling between 11.14 and 10.5 ^{14}C ka BP. A slight warming recorded in the uppermost glacial-marine sediments was interrupted by an inferred jökulhlaup event emanating from glacier ice on the Western Volcanic Zone. Retreat of the ice margin from the sea sometime between *c.* 10.3 and 9.94 ^{14}C ka BP coincided with this event. The onset of postglacial marine sedimentation occurred along with increasing evidence of Atlantic water *c.* 9.94 ^{14}C ka BP and was interrupted by a short-lived Preboreal cooling of the Irminger Current *c.* 9.91 ^{14}C ka BP. Conditions similar to those today were established by 9.7 ^{14}C ka BP.

Anne Jennings (e-mail: jenninga@spot.colorado.edu), James Syvitski, Linda Gerson and John Andrews, Campus Box 450, INSTAAR and Department of Geological Sciences, University of Colorado, Boulder, CO 80309-0450 USA; Karl Grönvold, Nordic Volcanological Institute, Grensásvegur 50, 108 Reykjavík, Iceland; Áslaug Geirsdóttir, Department of Geosciences, University of Iceland, 101 Reykjavík, Iceland; Jórunn Hardardóttir, Science Institute, University of Iceland, Dunhagi 3, 107 Reykjavík, Iceland; Sveinung Hagen, Institute of Geology and Biology, University of Tromsø, 9037 Tromsø, Norway; *received 25th May 1999, accepted 9th February 2000*

Iceland is located in a climatically sensitive geographic position relative to atmospheric circulation and the present-day marine arctic and polar fronts (Fig. 1). Large changes in the positions of the marine polar front mapped for the last deglaciation (Ruddiman & Macintyre 1981) have also been observed in the latest Pleistocene to Holocene sediments preserved in Iceland (Rundgren 1995; Ingólfsson *et al.* 1997). The extent and activity of glaciers in Iceland from the Last Glacial Maximum (LGM) to *c.* 9 ka were affected by changes in the position of the polar front (e.g. Ingólfsson & Norddahl 1994). The lack of radiocarbon dates on land during the LGM indicates that Iceland was largely ice covered, and that the ice-sheet margins were somewhere offshore. The ice extent during the LGM is often assumed to have been near the shelf-slope break, although there is no firm, dated evidence of this assumption (Denton & Hughes 1981; Ingólfsson & Norddahl 1994; Andrews *et al.* 2000). Radiocarbon dating of uplifted glacial-marine deposits and lake sediments indicates a stepwise retreat of the ice margins from the contemporaneous periphery of Iceland from *c.* 12.7 to *c.* 9.7 ^{14}C ka BP (Ingólfsson & Norddahl 1994 and references therein; Geirsdóttir *et al.* 1997). Ingólfsson & Norddahl (1994) suggested that deglaciation began sometime before 13 ka BP in response to climatic amelioration or sea-level rise, but the evidence for the earliest part of the deglaciation must be located offshore. Thus, there is a gap in the information about the glacial history of Iceland between the LGM and 12.7 ^{14}C ka BP, the earliest evidence of the ice margin on land. In addition, there is a lack of continuous, well-dated, high-resolution records of the changes in environmental conditions during deglaciation.

The purpose of this article is to present a continuous high-resolution paleoenvironmental record of deglaciation of the southwest Iceland shelf between 12.7 and 9.4 ^{14}C ka BP (Fig. 1) based on data collected on cruise HU93030 of the research vessel *C.S.S. Hudson*. These data include high-resolution seismic reflection profiles tied to sedimentological, tephra, and foraminiferal analyses of radiocarbon-dated core 93030-006 LCF (Long Coring Facility), a giant piston core from Jökuldjup, Faxaflói Bay (Fig. 1).

Physical setting

Jökuldjúp is a bathymetric depression in outer Faxaflói Bay, southwest Iceland shelf (Fig. 1). The Irminger

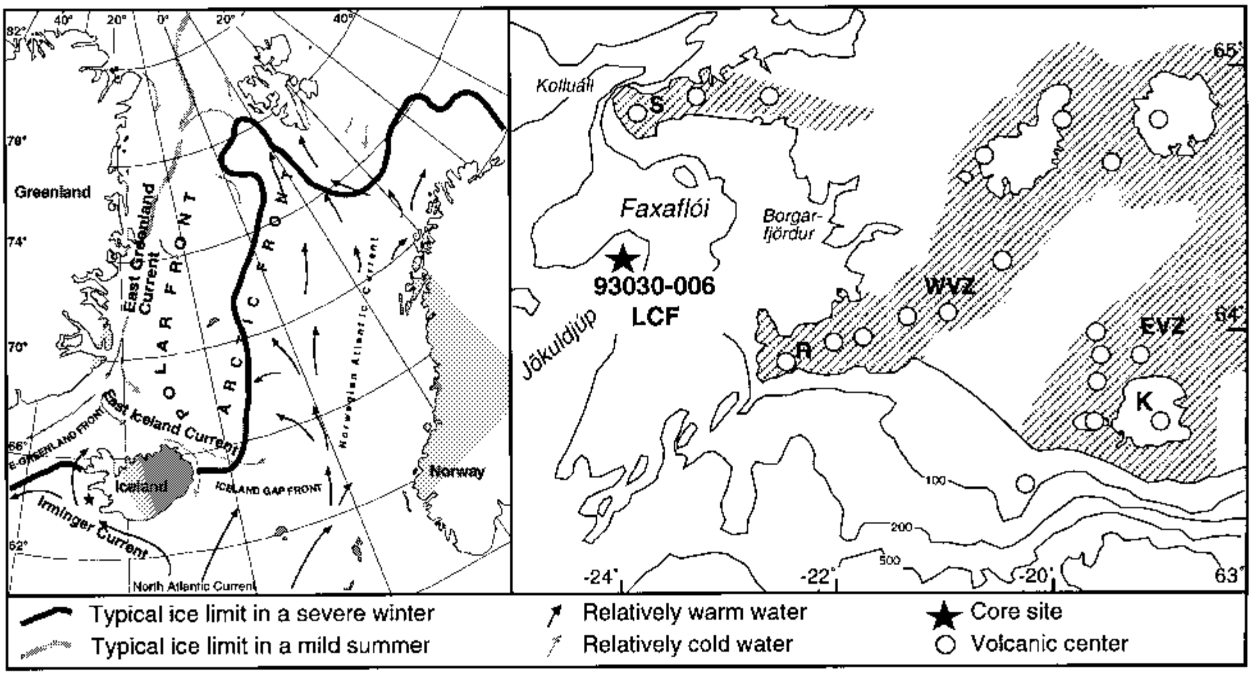

Fig. 1. Left: Map showing location of Iceland relative to surface currents and sea-ice limits (Hurdle 1986). Right: Map of southwestern Iceland showing the bathymetry of the shelf; the volcanic zones are demarcated by gray hatched lines, with WVZ and EVZ denoting Western and Eastern Volcanic Zones. Volcanic centers and associated fissure swarms are shown as open circles. The locations of Katla (K), Snaefellsnes Peninsula (S), Reykjanes Peninsula (R) and core 93030-006 LCF are also shown.

Current, a branch of the North Atlantic Current, carries warm, saline Atlantic water over the site (Fig. 1). Temperature and salinity measurements in Faxaflói Bay show a well-mixed water column with salinities of 35‰ and temperatures below 50 m of 7°C (Helgadóttir 1984; Asprey *et al.* 1994).

Faxaflói Bay is bounded to the south by the Reykjanes Peninsula and to the north by the Snaefellsnes Peninsula (Fig. 1). The Reykjanes Peninsula forms part of the Western Volcanic Zone (WVZ) of Iceland, which is characterized by active fissure volcanism of tholeiitic affinities (Jakobsson & Peters 1979). The Snaefellsnes Peninsula, on the other hand, forms a part of a volcanic zone, which was active mainly during the Pliocene and early to middle Pleistocene (Fig. 2; Sæmundsson 1979; Lacasse *et al.* 1996). The Katla subglacial volcanic system, which is located within the Eastern Volcanic Zone (EVZ) of Iceland, has been shown to be the source of both the basaltic and rhyolitic components of the Vedde Ash, a major component of Ash Zone I in the North Atlantic (Lacasse *et al.* 1995; Grönvold *et al.* 1995), which was erupted in *c.* 10.3 ka BP (Bard *et al.* 1994; Birks *et al.* 1996).

Previous work on the southwest Iceland shelf

Helgadóttir (1984) presented the first study of marine cores on the southwest Iceland shelf. She analyzed the sedimentology and foraminiferal stratigraphy of five gravity cores, from a depth-transect in Jökuldjúp, Faxaflói Bay. At the time of her study, accelerator mass spectrometry (AMS) dating was in its earliest phases, so no radiocarbon dates were available. However, recent AMS dating of these cores indicates that the oldest record extends to 10.6 ka BP (Helgadóttir pers. comm. 1999). The sediments in these cores are pebbly mud with an arctic faunal assemblage prior to *c.* 10.5 ka BP, changing to bioturbated mud with a boreal fauna by 9.3 ka BP. Syvitski *et al.* (1999) interpreted the history of glaciation of the southwest Iceland shelf using high-resolution seismic reflection profiles collected during *C.S.S. Hudson* cruise 93030, and Hagen (1995) presented a paleoceanographic study of the Holocene sediments from Jökuldjúp using cores 93030-006 TC (trigger core) and the upper 2.8 m of the 93030-006 LCF.

Based on the interpretation of seismic profiles, ice-marginal deposits have been reported at the southern and southwestern shelf edge, and at intermediate positions in Faxaflói Bay, as shown in Fig. 2 (Egloff & Johnson 1979; Helgadóttir 1984). Farther to the north, Ólafsdóttir (1975) mapped a 100-km long bathymetric ridge near the shelf-slope break on the outer margin of the Látra Bank (Fig. 2). This feature is assumed to be an end moraine, marking the maximum Weichselian ice margin at about 18 ka BP (Ólafsdóttir

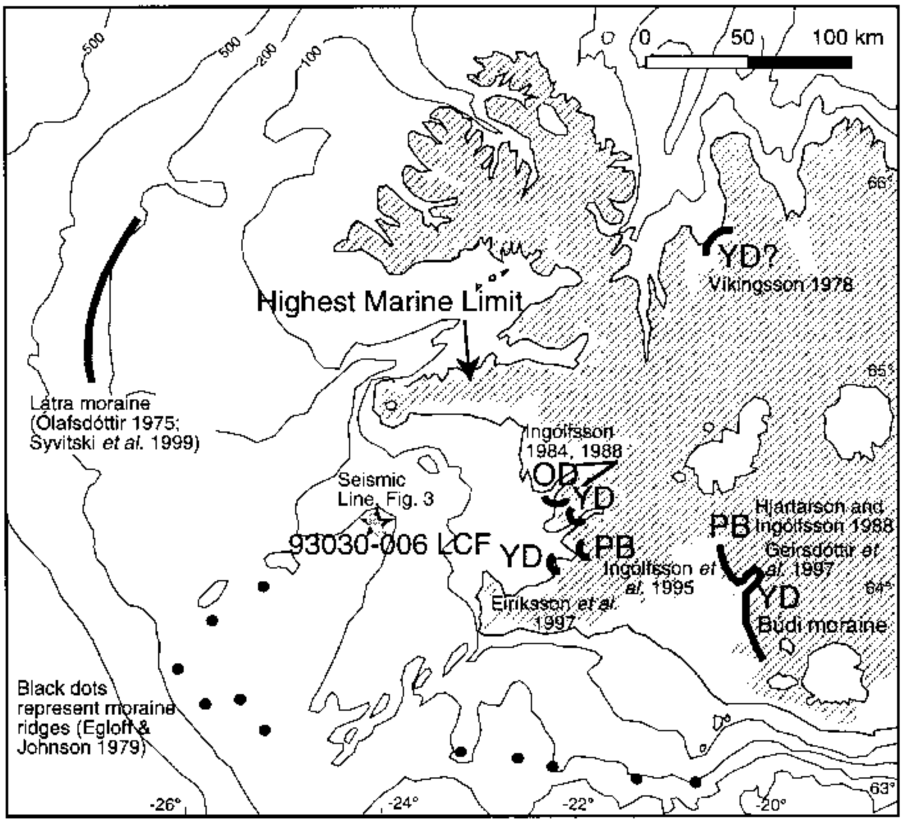

Fig. 2. Map of southwestern Iceland showing bathymetry, ice marginal features on the shelf, Older Dryas (OD), Younger Dryas (YD) and Preboreal (PB) ice margins and the maximum marine limit (demarcated by gray hatched lines) between 10.3 and 9.6 ka BP. The location of core 93030-006 LCF and the seismic profile in Fig. 3 are also shown.

1975; Einarsson & Albertsson 1988; Ingólfsson 1991; Syvitski *et al.* 1999). Syvitski *et al.* (1999) suggested that a moraine in Kolluáll Trough, slightly north of core 93030-006 LCF marks a stillstand in the overall retreat of ice from the last glacial maximum position (Fig. 1). None of the offshore moraine-inferred accumulations has been directly dated (cf. Andrews *et al.* 2000).

Sea-level studies have been used to constrain the history of deglaciation around Iceland (e.g. Rundgren *et al.* 1997). The highest marine limit varies as a result of differing glacial loads. A limit of 110 m in southern Iceland is associated with the Younger Dryas/Preboreal age Búdi morainal complex (Hjartarson & Ingólfsson 1988; Geirsdóttir *et al.* 1997; Ingólfsson *et al.* 1997; Fig. 2). The marine limit decreases to between 60 and 80 m in western Iceland (Ingólfsson *et al.* 1995). A local marine limit of 80 m in western Iceland has been related to a glacial advance to the outer coast during the Older Dryas, the Skipanes event (Ingólfsson 1988; Fig. 2). A regional marine limit of 60 m in western and southwestern Iceland dates to retreat from a Younger Dryas readvance, which Ingólfsson (1988) refers to as the Skorholtsmelar event. A rapid relative fall in sea level from 40 to −25 m in Faxaflói Bay (Thors & Helgadóttir 1991) dated sometime between 10.3 and 9 ka BP attests to the very rapid isostatic rebound during and after the deglaciation (Ingólfsson *et al.* 1997). However, sediment studies within Lake Hestvatn (42 m a.s.l.) and the Búdi morainal complex in the southern lowlands of Iceland indicate that the lowlands were submerged until approximately 9.0 ka BP, based on the transition from marine sediment to lacustrine sediment at −27 m within Lake Hestvatn (Geirsdóttir *et al.* 1997). Jökulhlaups played a major role in the final collapse of the ice from the Búdi moraine complex (Geirsdóttir *et al.* 1997).

The core in this study, 93030-006 LCF, lies spatially and temporally between the potential LGM position on the outer shelf and the Younger Dryas/Preboreal Búdi moraine complex on land, and thus should record the events and environmental conditions that occurred between the formation of these features.

Materials and methods

Huntec and Airgun seismic reflection records and sediment cores were among the types of data that were collected on the 1993 *C.S.S. Hudson* cruise (Asprey *et al.* 1993). Details concerning the geophysical data are given in Syvitski *et al.* (1999). A series of different types of cores was taken at a single coring site in Faxaflói Bay in order to ensure collection of the complete sediment section, including a box core, Lehigh core, and a Long Coring Facility (LCF) core, which comprises an instrumented piston corer and a trigger corer. Core 93030-006 LCF was collected from 254 m water depth at 64°17.06′N, and 24°12.42′W. The 13.17-m long core was split in half longitudinally during the cruise. The half to be archived was visually described for color and sedimentary structures (Hein, in Asprey *et al.* 1993), and photographed. The working half of the core was immediately sampled for bulk density at 20-cm intervals. Foraminiferal and sediment subsamples spanning a 2-cm interval were taken every 20 cm, except where lithofacies changes occurred; in these cases, samples were taken above and below the lithofacies change. The archive half of the core was X-rayed at the Bedford Institute of Oceanography Core Repository.

Foraminiferal samples from 93030-006 LCF were prepared at the Institute of Arctic and Alpine Research (INSTAAR) using the methods detailed elsewhere (Jennings *et al*. 1998). Benthic and planktonic foraminifera were picked from the >125 μm fraction and were identified using a stereomicroscope. Benthic species percentages and planktonic and benthic foraminiferal abundances were calculated. Climatic tolerances of the benthic species were determined from previous work on the Iceland shelf (Helgadóttir 1984; Jennings *et al.* 1994) and elsewhere in the northern North Atlantic (cf. Knudsen *et al.* 1996). Planktonic foraminifera were identified to species, but there were generally too few present in the benthic foraminiferal splits to allow percentages to be calculated. However, in 12 of the samples, as many as 100 planktonic foraminifers could have been obtained by examining the entire sample, and in the uppermost two samples of the LCF core, there were abundant planktonic foraminifers.

Sedimentological analyses including grain size, carbonate content, organic carbon content, and mass-magnetic susceptibility were completed at INSTAAR. The grain-size distributions of the samples were measured using a combination of dry sieving (Ro-tap) for particle sizes greater than 44 μm, and sedimentation (Sedigraph 5000D Particle Size Analyzer) for particles smaller than 44 μm. The carbonate content was measured using the Chittick apparatus (Dreimanis 1962).

Tephra shards from a tephra layer at 2.78 m in the core were isolated from the bulk >125 μm sand fraction prepared for foraminiferal analysis. The chemical composition of 47 shards was analyzed by microprobe at the Nordic Volcanological Institute, Iceland.

AMS radiocarbon dates were obtained using the University of Arizona Tandem Accelerator Mass Spectrometer. All reported ages were corrected for an assumed marine reservoir age of 400 years, in order to be consistent with most other Icelandic studies (e.g. Sveinbjörnsdóttir *et al.* 1993). However, this correction undoubtedly varied during the last deglaciation (Bard *et al.* 1994).

Results

Seismic stratigraphy

Airgun profiles in Jökuldjúp indicate over 80 m of sediments above volcanic bedrock. Syvitski *et al.* (1999) documented three intervals of ice-contact sediments and glacial-marine muds within this sequence, suggesting at least three glacial advance/retreat cycles in the basin. The higher resolution Huntec profiles provide detail of the uppermost cycle (Fig. 3).

Acoustically unstratified sediments with irregular topography, interpreted as ice-contact sediments, are conformably overlain by 13 m of glacial-marine sediments (Fig. 3). The glacial-marine unit is characterized by distinctive low to medium tone, weak to moderate acoustic stratification, and a conformable bedding style in which basal topography underlying the unit is translated through internal reflectors to the unit surface.

A two-part unit overlies the glacial-marine unit and is called the ‘transitional unit’ (Fig. 3). The lower part of the transitional unit comprises a reflector that conforms to the surface of the underlying glacial-marine unit. This reflector’s coherency and strength gradually weaken into the deeper water of the trough. The overlying part of the transitional unit has an irregular surface and thickens to up to 6 m in the deeper areas of the shelf trough. It has moderate tone and lacks internal acoustic stratification. The acoustic characteristics of the upper part of the transitional unit strongly resemble the characteristics of debris flows. Core 93030-006 LCF penetrates the transitional unit in a location where it is very thin. In the core this correlates to a 0.76-m thick, tephra-bearing, sandy and pebbly interval consisting of two distinct sediment types.

The transitional unit is overlain by an acoustically stratified unit with moderate lateral thickness variation that represents postglacial marine sediments (Fig. 3). The postglacial unit consists of moderately weak, closely spaced reflectors of medium tone. The unit onlaps onto the margins of the shelf trough. The exposed sea floor of the postglacial unit has circular pockmarks, 80 to 100 m in diameter, as observed in high-resolution sidescan sonar images. The pockmarks may be active sites of gas or water escape.

Lithostratigraphy

Stratigraphic correlation of the other cores (box core, Lehigh core and trigger core) taken at the same site and comparison with the Huntec data indicate that core 93030-006 LCF collected sediments to within one meter of the contact between glacial-marine and ice-contact sediments, but that it bypassed the upper 3.20 m of the sediment section (Fig. 3). Thus, the 13.17-m long core 93030-006 represents from 3.20 to 16.37 m of the Huntec profile across the site (Fig. 3). The upper 1.10 m of sediment in 93030-006 LCF was disturbed

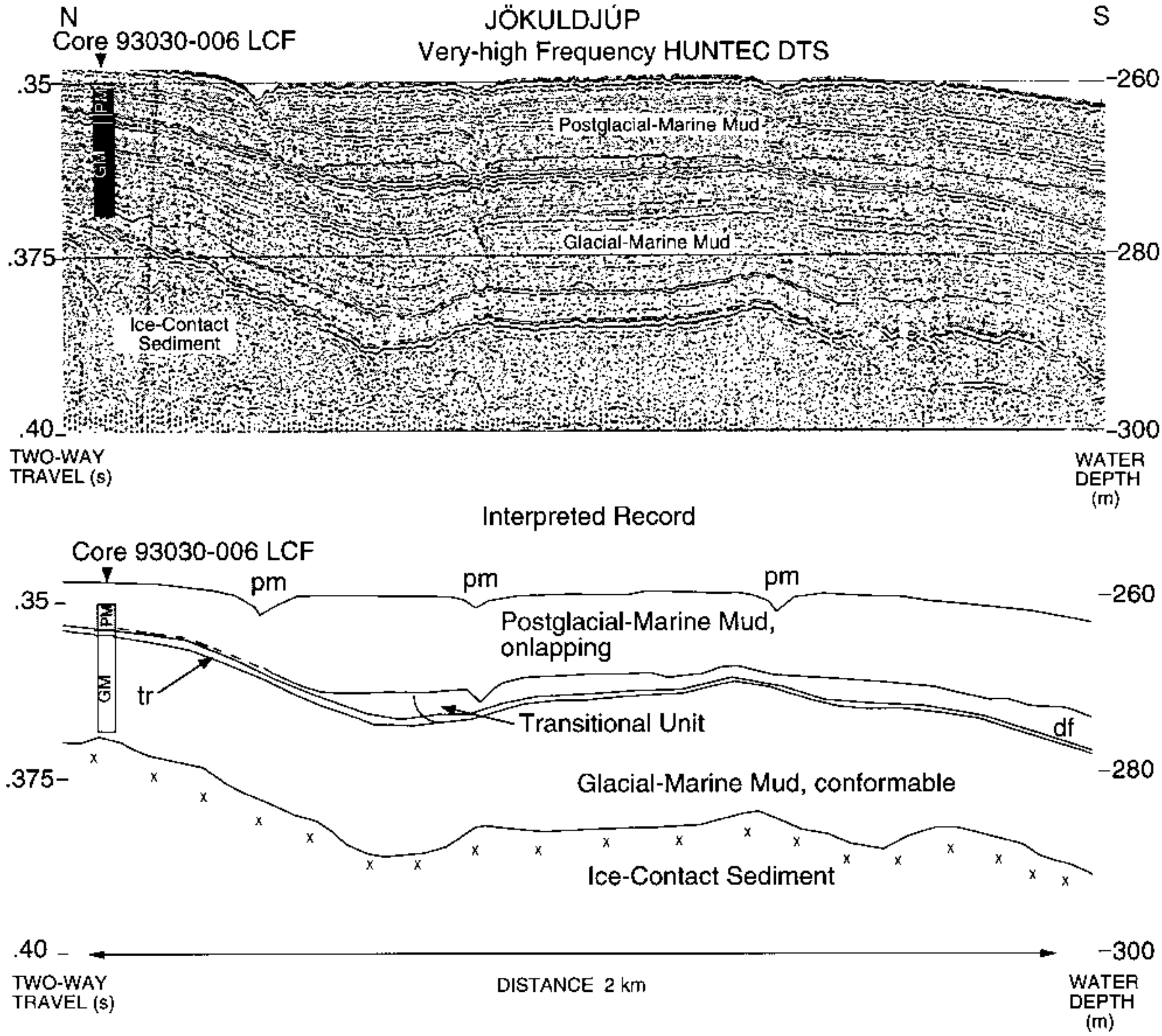

Fig. 3. Huntec profile (upper) and interpretation of the Huntec profile (lower) in Jökuldjúp showing placement of 93030-006 LCF within the profile (PM = postglacial marine unit; GM = glacial-marine unit in the core); pm = circular pock marks, 80–100 m in diameter; df = debris flow deposit thickening into deeper water; tr = transitional reflector weakening into deeper water and marked by 30% sand content.

during coring and was not sampled. Therefore, our analyses on the core begin at 1.10 m, which is equivalent to 4.30 m below the sea floor. The lithofacies log and sedimentological data are presented in Fig. 4.

13.17–10.7 m, Fmd: Bioturbated gray (5Y on the Munsell color chart) clayey silt with small (2 to 8 mm diameter) dropstones.

10.7–3.02 m, Fsd: Bioturbated gray (5Y on the Munsell color chart) clayey silt with small (2 to 8 mm diameter) dropstones and indistinct stratification.

These two lithofacies correspond with the glacial-marine seismic unit interpreted on the Huntec high-resolution seismic profile. No colorless platey bubble-wall tephra shards were observed, but brown tephra was abundant in the sand fraction. The ice-rafted detritus (IRD) content, defined as the weight percent of the $>$1 mm grains, is quite low throughout this interval, but rises above 9 m depth in the core, and reaches peak percentages between 7 and 5 m (Fig. 4). The total carbon percentages follow a similar trend with an interval of higher percentages between 9 and 5 m, possibly reflecting a decrease in sedimentation rate over this interval (Syvitski *et al.* 1990).

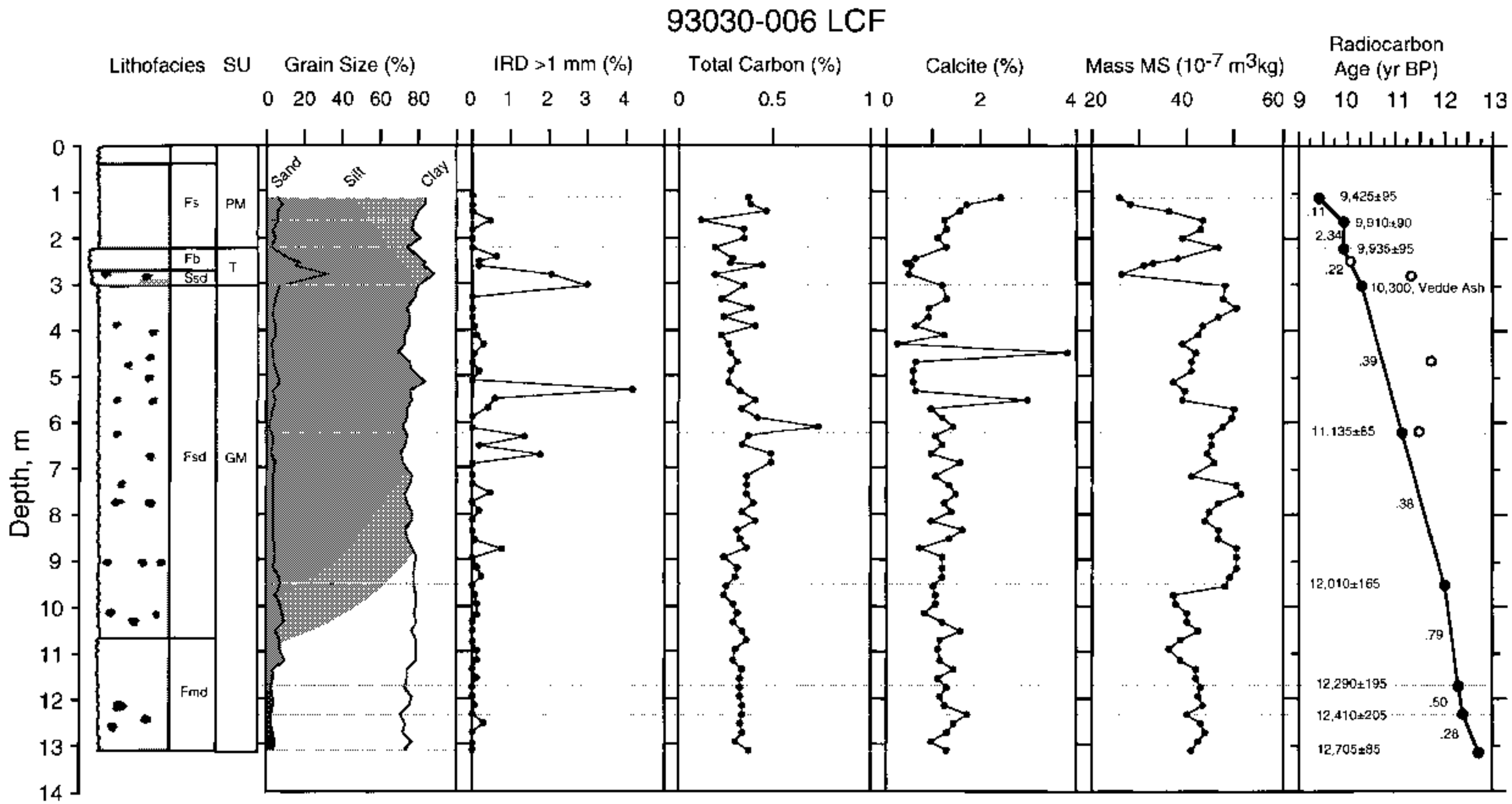

Fig. 4. Lithostratigraphic log showing lithofacies units, seismic units (SU, with GM = glacial marine unit; T = transitional unit; PM = postglacial marine unit), grain size, weight percentage of >1 mm grains interpreted as ice rafted detritus (IRD), mass magnetic susceptiblity (MS), total carbon, calcite and radiocarbon dates (see Table 1). The dates used in the final chronology are represented as black dots. Those eliminated from the final chronology (see text) are shown as gray dots. Sedimentation rates calculated between dated levels are indicated along the lines connecting the dates. Lithofacies codes: Fs = stratified mud; Fb = bioturbated mud; Ssd = stratified sand with dropstones; Fsd = stratified mud with dropstones; Fmd = massive mud with dropstones.

Table 1. AMS radiocarbon dates from 93030-006 LCF.

Depth (cm)	Sample no.	Reported age	Reservoir corrected age	Species dated
1.10–1.12	AA-15701	9825 ± 95	9425 ± 95	*Melonis barleeanus*[1,2]
1.63–1.65	AA-15702	10 310 ± 90	9910 ± 90	*M. barleeanus* [1,2]
2.22–2.23	AA-15703	10 335 ± 95	9935 ± 95	Mixed benthic species[1,2]
2.52	AA-27262	10 430 ± 60	10 030 ± 60	*N. labradorica*[1,2]
2.78	AA-20732	11 730 ± 305*	11 330 ± 305*	*N. labradorica* & *I. helenae*[2]
4.70	AA-20733	12 130 ± 290*	11 730 ± 290*	*N. labradorica* & *E. excavatum* f. *clavata*[2]
6.22	AA-19915	11 830 ± 125*	11 430 ± 125*	Ophiuroid ossicles[2]
6.25	AA-12897	11 535 ± 85	11 135 ± 85	*E. excavatum* f. *clavata*[2]
9.55	AA-20734	12 410 ± 165	12 010 ± 165	Ophioroid ossicles[2]
11.75	AA-20735	12 690 ± 195	12 290 ± 195	*N. labradorica*[2]
12.35	AA-20736	12 810 ± 205	12 410 ± 205	*E. excavatum* f. *clavata*[2]
13.17, cc**	AA-12896	13 105 ± 85	12 705 ± 85	*N. labradorica*[2]

[1] Hagen (1995); [2] Manley & Jennings (1996); * Date excluded from the final ^{14}C chronology; ** Core cutter.

3.02–2.71 m, Ssd: Stratified, dropstone-bearing sand. The sand fraction consists of both basaltic (black and brown) and rhyolitic (colorless platey bubblewall) tephra shards and black basaltic rock fragments. Stratification is pronounced and burrows are absent. A 0.5-cm thick sand layer occurs at 2.96 m. Large dropstones of up to 3 cm in diameter are concentrated between 2.88 and 2.79 m. A sandy silt (32.4% sand) tephra-bearing layer lies between 2.78 and 2.71 m.

2.71–2.26 m, Fb: bioturbated sandy silt and clayey silt, with relatively high sand content between 12.1 and 17.2%. Sand fraction consists of both basaltic (black and brown) and rhyolitic (colorless platey bubblewall) tephra shards and black basaltic rock fragments. IRD is rare or absent.

These two sandy sediment lithofacies, Ssd and Fb, correspond with the two-part transitional seismic unit that separates the glacial-marine sediments from the postglacial marine unit on the Huntec profile (Fig. 3). Both units have high contents of volcanic ash, expressed in the high sand percentages, but the differences in IRD content and stratification suggest that the origins of the two subfacies are different. The lower subfacies (Ssd) corresponds with the lower unit of the transitional seismic units. The overlying massive, tephra-rich subfacies (Fb) corresponds with the debris-flow unit.

2.26–1.10 m, Fs: Massive to crudely stratified dark-gray clayey silt and silt with some burrowing structures. Dropstones were observed only at 1.63 m.

This lithofacies corresponds with the lower part of the postglacial marine seismic unit.

Tephra analysis

Chemical analyses of tephra shards from the tephra layer at 2.78 m, the stratified, sandy, pebbly tephra layer (Ssd), showed three distinct chemical compositions (Fig. 5; Table 2). Two of these components, basaltic (basic) and rhyolitic (silicic) glass shards, have chemical compositions consistent with the end members of the Vedde Ash (Norddahl & Haflidason 1992; Grönvold *et al*. 1995). These grains constitute the earliest observed occurrence of colorless, platey, bubblewall shards in the core, suggesting that the glacial-marine sediments below 3.02 m probably were deposited before the eruption of the Vedde Ash from Katla, southern Iceland, at about 10.3 ka BP (Bard *et al.* 1994; Mangerud *et al.* 1984). A third chemical component distinguished at 2.78 m is basaltic grains, with a composition similar to the WVZ in southwest Iceland (Fig. 2).

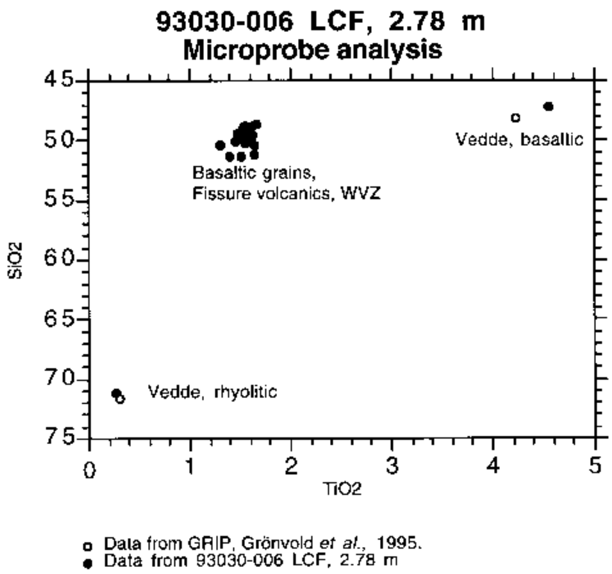

Fig. 5. Microprobe compositional data of tephra shards at 2.78 m in 93030-006 LCF (Table 2) compared with the composition of the basaltic and rhyolitic grains in GRIP ice core (Grönvold *et al.* 1995).

Table 2. Microprobe compositional analysis of tephra in Core 93030-006 LCF, 2.78 m.

	SiO_2	TiO_2	Al_2O_3	FeOtotal	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
Vedde/Skogar, rhyolitic grains [25]	71.1	0.27	13.7	3.8	0.13	0.25	1.38	5.44	3.3	0	99.37
Vedde/Skogar, basaltic grains [5]	47.2	4.54	12.8	14.6	0.23	5.03	10.2	2.87	0.59	0.55	98.6
Fissure volcanics; basalt grains	51.2	1.65	12.9	12.3	0.21	6.2	11.4	2.44	0.18	0.05	98.52
	51.4	1.51	13.3	12.4	0.26	6.54	11.7	2.2	0.03	0.08	99.33
	51.4	1.4	13.2	12.4	0.22	6.68	11.6	2.25	0.03	0.09	99.25
	50.4	1.65	13.6	10.2	0.2	6.76	14.2	1.94	0	0	99.06
	49.5	1.47	14	11.2	0.2	6.8	12.5	2.17	0.11	0.03	97.98
	50.4	1.31	13.6	11.8	0.23	7.05	12.3	2.04	0.02	0.09	98.8
	49.6	1.49	13.9	11.3	0.19	7.18	12.5	1.94	0.11	0.01	98.2
	50.1	1.46	13.4	11.3	0.22	7.3	12.6	2.38	0.12	0.15	98.95
	50.3	1.54	13.8	11.6	0.21	7.32	12.6	2.08	0.1	0.07	99.6
	49.1	1.61	14.1	11.5	0.2	7.42	12.5	2.07	0.09	0.01	98.49
	48.9	1.63	13.3	11.1	0.16	7.65	12.4	2.09	0.09	0.01	97.41
	49.1	1.53	14.2	11	0.21	7.72	12.4	2.1	0.11	0.06	98.41
	49	1.53	15	11	0.15	7.78	12.5	2.05	0.07	0.05	99.04
	48.9	1.55	13.3	11.3	0.21	7.83	12.5	2.12	0.08	0.04	97.75
	49.8	1.58	14.1	11.3	0.19	7.92	12.4	2.17	0.13	0.09	99.75
	48.6	1.67	14.3	10.9	0.18	7.99	12.3	2.2	0.06	0	98.2
	49.7	1.63	15.2	11.1	0.17	8.13	12.4	1.96	0.1	0.06	11.42
Vedde/Skogar	71.7	0.31	13.5	3.93	0.11	0.2	1.14	5.3	3.34	0	99.53
(Grönvold *et al*. 1995)	48.2	4.23	11.8	14.1	0.2	4.54	9.31	3.2	0.9	0	96.48

Chronology and sedimentation rates

Twelve AMS radiocarbon dates were obtained on benthic foraminifera (n = 10) and echinoid ossicles (n = 2) (Hagen 1995; Manley & Jennings 1996) (Table 1). Three of the dates were stratigraphically reversed compared to underlying dates and therefore these three dates were excluded from the final chronology (Table 1). Given the offsets in the radiocarbon time-scale during the deglaciation, caused by changes in ocean circulation and radiocarbon production, we did not calibrate our radiocarbon dates to a calendar time scale (e.g. Björck *et al.* 1996). This approach is consistent with other deglacial and early Holocene chronologies on Iceland (e.g. Ingólfsson *et al.* 1997; Geirsdóttir *et al.* 1997). The first observation of Vedde Ash at the base of lithofacies Ssd, the transitional unit between the glacial-marine and postglacial seismic units, provides a maximum age for lithofacies Ssd of 10.3 ka BP (Birks *et al*. 1996). We consider this to be a maximum age because we recognize that the Vedde Ash in lithofacies Ssd may not represent a primary ash-fall deposit. Prevailing winds during the time of the Vedde eruption may have excluded the delivery of Vedde Ash to Faxaflói Bay by ash fall, and the Vedde Ash may have been delivered later by other processes such as rafting on disintegrating glacier ice (cf. Larsen *et al.* 1998). A ^{14}C date on *N. labradorica* and *Islandiella* spp. within lithofacies Ssd at 2.78 m was stratigraphically reversed, indicating reworking of older materials during deposition of lithofacies Ssd. The date of 10.03 $\pm$ 60 ka BP on *N. labradorica* from 2.52 m in lithofacies Fb is not the most conservative upper age constraint on lithofacies Ssd because although it is not stratigraphically inverted, it is within sediments interpreted as debris flow. Therefore, the upper age used for lithofacies Ssd and Fb (the two lithofacies within the transitional seismic unit) is the date of 9.94 $\pm$ 95 ka BP, at 2.22 to 2.23 m, only 3 cm above lithofacies Fb. Therefore, lithofacies Ssd (and the transitional seismic unit) must have been deposited sometime between 10.3 and 9.94 ka BP. Sample ages in the core were calculated by linear extrapolation between dated levels, and we assign the age of 10.3 ka BP to the base of lithofacies Ssd. We do not attempt an estimate of the errors involved with linear extrapolation as described in Andrews *et al.* (1999).

Sedimentation rates were calculated between dated levels in centimeters per radiocarbon years, and are therefore subject to errors from radiocarbon plateaux and potential changes in the marine reservoir age. Sedimentation rates rise from 0.28 cm/yr at the base of the core to higher values between 12.4 and 12.0 ka BP (0.50 to 0.79 cm/yr), and intermediate values (0.38 to 0.39 cm/yr) between 9.55 and 3.02 m (Fig. 4). With these rapid sedimentation rates, 20-cm sampling intervals in the glacial-marine sediments represent between 25 and 72 ^{14}C years.

Using a maximum age of 10.3 ka BP at the base of lithofacies Ssd and a date of 9.94 ka BP above lithofacies Fb, sediments in the transitional unit were deposited with an average sedimentation rate of

0.22 cm/yr. However, the sedimentary structures and the high, variable sand contents suggest that there were probably large changes in sedimentation rate over the time interval represented by the transitional seismic unit.

The sedimentation rates in lithofacies Fs, the base of the postglacial marine seismic unit, rise to very high values up to 2.34 cm/yr in the early Preboreal chronozone. The high rates must reflect the influence of the radiocarbon plateau, but there is independent evidence for rapid sedimentation including the presence of IRD and a short-lived return to glacial-marine foraminiferal fauna. The sedimentation rate falls to 0.11 cm/yr in the uppermost part of the core, soon after 9.9 ka BP.

Foraminiferal biostratigraphy

Seventy-two benthic and four planktonic species were identified in the core. Eight informal assemblage zones were defined based on changes in the benthic foraminiferal faunas. These assemblage changes provide important information on the paleoenvironmental conditions during the deglaciation (Figs 6 and 7; Table 3). In the glacial-marine unit (Assemblage Zones 1 through 5), the two common glacial-marine species in the northern hemisphere, *Cassidulina reniforme* and *Elphidium excavatum* f. *clavata*, dominate the foraminiferal faunas, supporting the acoustic and lithofacies data that suggest these are glacial-marine sediments (Fig. 6).

Assemblage Zone 1, Glacial-Marine Unit: 13.10–11.35 m (12.68–12.24 ka BP).

The benthic fauna contains a pronounced component of species with boreal and slope-dwelling environmental significance, including *Pullenia osloensis, Cassidulina neoteretis*, and *Stainforthia concava*. *P. osloensis* and *C. neoteretis* are rare or absent for the remainder of the core, only returning at very low percentages in the postglacial sediments. *C. neoteretis* has been recognized as an early postglacial immigrant into shelf troughs in the Barents Sea, where it has been associated with the inflow of Atlantic-derived waters (Lubinski *et al.* 1996; Hald & Aspeli 1997). *E. excavatum* f. *clavata* rises from low values of *c.* 10% to a pronounced peak of almost 70% at about 12.4 ka BP. The *E. excavatum* f. *clavata* peak coincides with the first increase in sedimentation rate at about 12.4 ka BP. The concentration of benthic foraminifera is relatively low throughout the interval. The ratio of the Arctic planktonic foraminifer, *Neogloboquadrina pachyderma* sinistral to the total planktonic fauna fluctuates widely, with the highest ratios corresponding to the rise in *E. excavatum* f. *clavata*.

Assemblage Zone 1 is interpreted to reflect a relatively strong presence of Irminger Current during the Bølling chronozone coincident with rapid deglaciation of the shelf. Conditions shifted from a strong Atlantic water influence, reflected in particular by the presence of Boreal species common in the Irminger Current today (Helgadóttir 1984; Jennings *et al.* 1994), to a strong glacial meltwater influence as indicated by the dominance of *E. excavatum* f. *clavata* (Hald *et al.* 1994) during an interval of increased sedimentation rate, and back to a strong influence of Atlantic water. Large swings in the ratio of Arctic to total planktonic fauna suggest fluctuating near-surface ocean conditions.

Assemblage Zone 2, Glacial-Marine Unit: 11.35–9.55 m (12.24–12.01 ka BP).

The distinguishing characteristics of this assemblage zone are a pronounced rise in *E. excavatum* f. *clavata* percentages and benthic foraminiferal concentrations. This zone coincides with an interval of rapid sedimentation rate from 12.29 to 12.01 ka BP. The end of this rapid sedimentation interval is marked by the abrupt decrease in *N. labradorica*, decreased *E. excavatum* f. *clavata*, and relative increases in *C. reniforme*, *Cibicides lobatulus*, *Astrononion gallowayi* and *Melonis barleeanus*. The ratio of *N. pachyderma* sinistral to the total planktonic fauna fluctuates widely.

Assemblage Zone 2, represents the end of the Bølling chronozone. The dominance of *E. excavatum* f. *clavata* reflects increased influence of glacier ice on the marine environment producing meltwater and increased sedimentation. Atlantic water continued to influence the shelf, as is shown by the presence of Boreal species. Continued fluctuations in the ratio of Arctic to total planktonic fauna suggest variable near-surface ocean conditions.

Assemblage Zone 3, Glacial-Marine Unit: 9.55–6.25 m (12.01–11.14 ka BP).

The benthic assemblage is dominated by *C. reniforme* until 7.55 m (11.48 ka BP) when *E. excavatum* f. *clavata* rises to high percentages. The glacial-marine species percentages together rise as high as 94% at 6.25 m (*c.* 11.14 ka BP). *A. gallowayi* and *C. lobatulus* percentages also rise over this interval, whereas *N. labradorica* percentages are very low. Boreal species, *M. barleeanus*, and *S. concava* co-occur fairly consistently until 6.25 m (11.14 ka BP) when these species essentially disappear from the assemblages. The ratio of *N. pachyderma* sinistral to the total planktonic fauna declines over this interval.

Assemblage Zone 3, coincides with the Older Dryas and Allerød chronozones. The dominance of *C. reniforme*, the rise in total carbon values and IRD and the slower sedimentation rate reflect distal glacial-marine conditions with diminished meltwater (cf. Polyak & Mikhailov 1996). Boreal species and other indicators of the influx of warm saline Atlantic waters show a weak varying influence of the Irminger Current along the shelf. The overall decrease in the ratio of Arctic to total planktonic foraminifers suggests warming of surface waters during this zone.

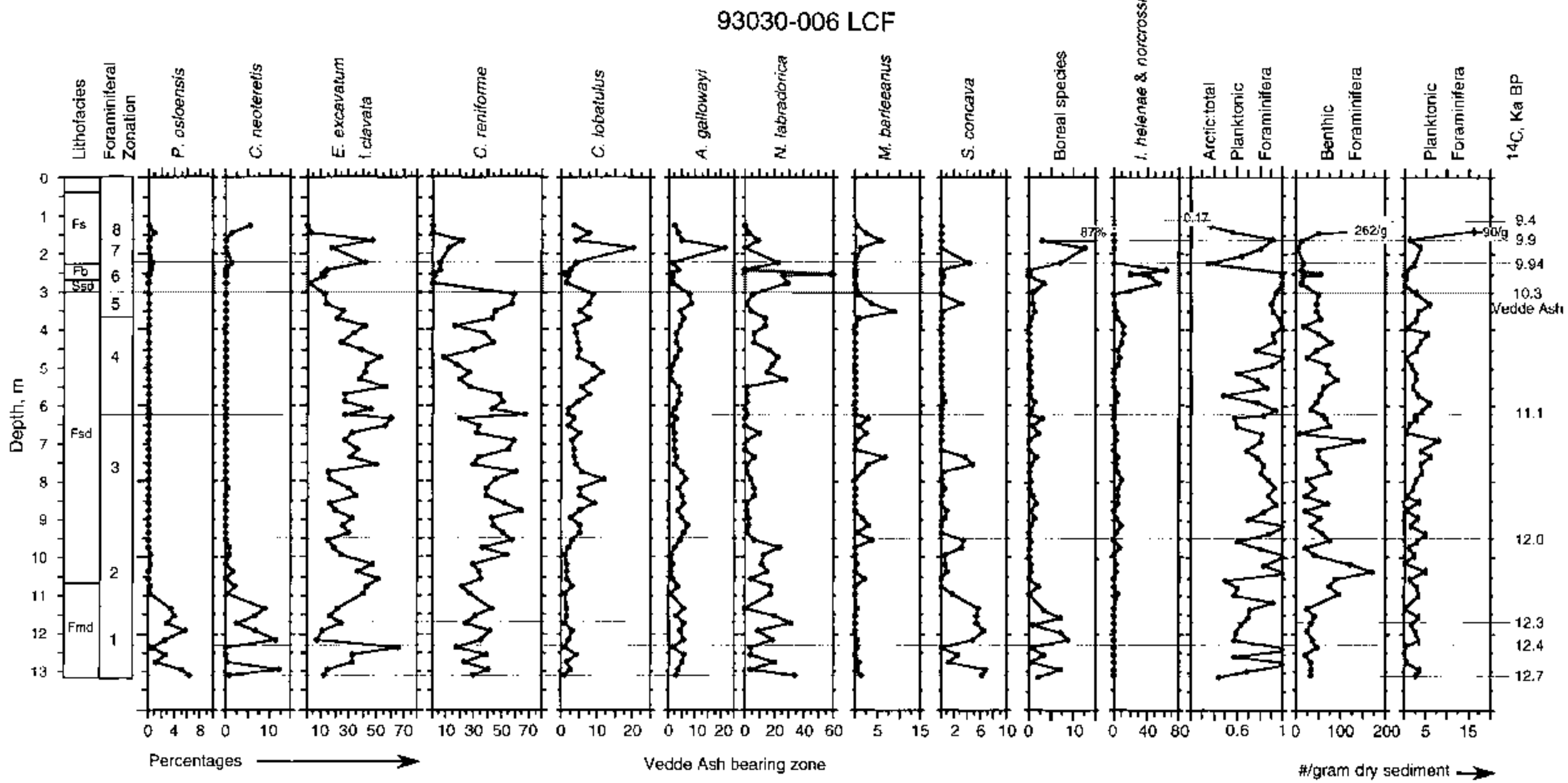

Fig. 6. Foraminiferal species data against lithofacies, foraminiferal zonation, and reservoir-corrected radiocarbon dates retained for final chronology. Species included in Boreal species are listed in Table 3. The gray box represents the Vedde Ash-bearing sediments of the transitional unit.

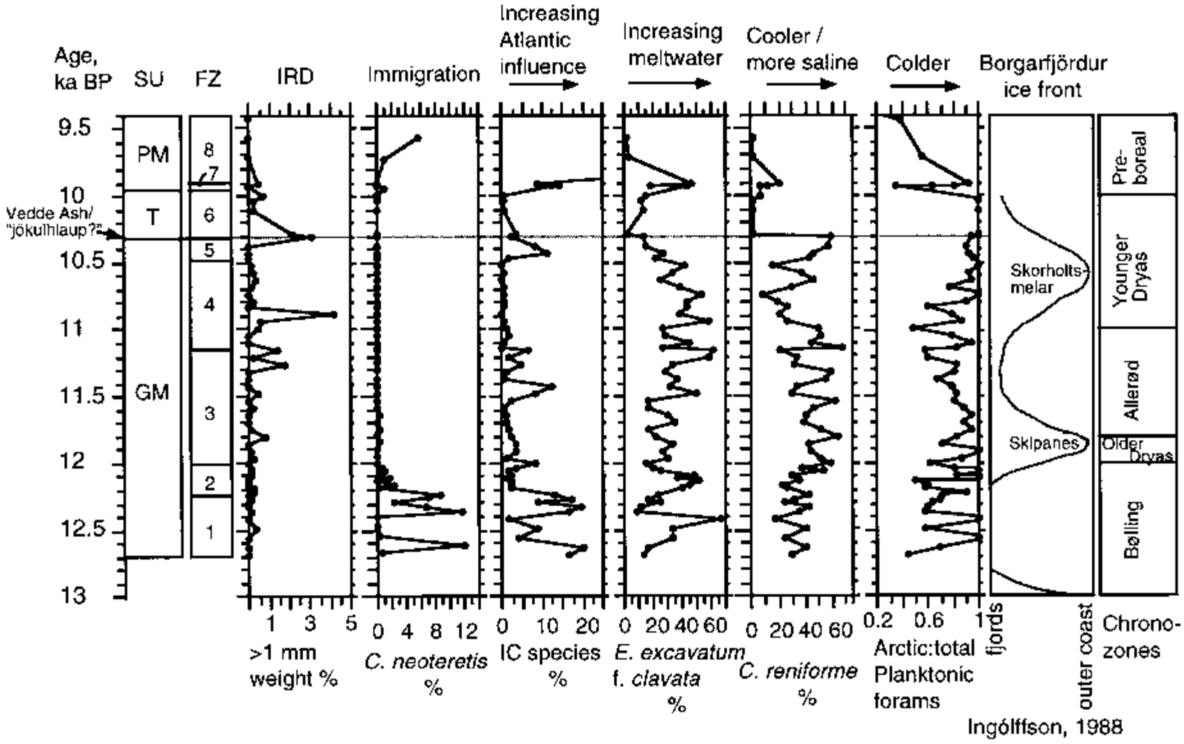

Fig. 7. Summary figure showing key environmental proxies of glacial influence and Atlantic water inflow in 93030-006 LCF against radiocarbon years and chronozones (Mangerud 1974). These records are compared with the local glacial record in Borgarfjördur showing a time-distance diagram of glacier advances and retreats from the fjords to the outer coast (Ingólfsson 1988). IRD as indicated by weight % of >1 mm grains; *C. neoteretis* as evidence of early immigration of slope-dwelling species after deglaciation; Atlantic water influence as shown by foraminiferal species indicative of Atlantic water carried in the Irminger Current (Boreal species as in Fig. 6, plus *M. barleeanus, P. osloensis, and S. concava*); turbid glacial meltwater indicated by *E. excavatum* f. *clavata*; cold, relatively higher salinity glacial-marine conditions indicated by *C. reniforme*; and cold sea surface conditions indicated by increasing ratio of Arctic (*N. pachyderma* sinistral) to the total planktonic forams. SU = seismic unit (PM = postglacial marine unit; T = transitional unit; GM = glacial-marine unit) and FZ = foraminiferal zonation.

Assemblage Zone 4, Glacial-Marine Unit: 6.25–3.70 cm (11.14–10.48 ka BP).

Over this interval, percentages of *C. lobatulus*, *A. gallowayi*, and the arctic shelf species *Islandiella helenae* and *I. norcrossi* rise. *E. excavatum* f. *clavata* decreases from values close to 60% at 5.50 m to values as low as 10% at 3.03 m. The trend in *C. reniforme* percentages is the opposite to that for *E. excavatum* f. *clavata*, rising from values as low as 10% to values close to 60% at 3.03 m. Although *N. labradorica* appears to be important over this interval, the stratigraphically reversed radiocarbon date at 4.70 m, which relied mainly on *N. labradorica*, suggests that this species is probably reworked between 5.30 and 3.70 m. The ratio of *N. pachyderma* sinistral to the total planktonic fauna fluctuates widely, but rises overall toward high values.

Assemblage Zone 4 coincides with the first half of the Younger Dryas chronozone. The abundant glacial-marine fauna, low percentages or absence of Boreal fauna, rising Arctic to total planktonic foraminiferal ratios and the continued high IRD reflect the onset of cooler ocean conditions with continued glacial influence.

Assemblage Zone 5, Glacial-Marine Unit: 3.70–3.02 m (10.48–10.3 ka BP).

Coinciding with the decline in *E. excavatum* f. *clavata* and the rise in *C. reniforme*, the percentages of boreal species, *M. barleeanus*, and *S. concava* increase. Over this same interval, IRD contents in the core fall to very low percentages (Fig. 4). The ratio *N. pachyderma* sinistral to the total planktonic fauna is high over this zone, but shows a slight decline to lower values corresponding with the rise in the boreal benthic species percentages.

Assemblage Zone 5 reflects decreasing glacial influence during the latter half of the Younger Dryas chronozone. Shifts in dominance from *E. excavatum* f. *clavata* to *C. reniforme* indicate changes to higher salinity conditions and diminished glacial meltwater (Hald & Steinsund 1996). Slight warming of the shelf began by 3.70 m (10.48 ka BP) marked by the slight rise

Table 3. Foraminiferal species list including the dominant taxa that comprise the 'Boreal' species in Fig. 6. The faunal province and paleoenvironmental significancce of each taxon is given from modern Iceland shelf foraminiferal assemblage data and the distributions of species within the eastern North Atlantic faunal provinces (see Helgadóttir 1984; Knudsen *et al*. 1996; Jennings *et al*. 1994).

	Faunal Province (paleoenvironmental interpretation)				
Benthic foraminiferal species	Boreal (Atlantic water in Irminger Current)	Transitional	Arctic (glacial marine)	Arctic	Indifferent
Angulogerina angulosa (Williamson 1858)	x				
Astrononion gallowayi Loeblich & Tappan 1953					x
Buccella frigida calida Cushman & Cole 1930	x				
Bulimina marginata d'Orbigny 1826	x				
Cassidulina laevigata d'Orbigny 1826	x				
Cassidulina neoteretis Seidenkrantz 1995		x			
Cassidulina obtusa Williamson 1858	x				
Cassidulina reniforme Nørvang 1945			x		
Cassidulinoides bradyi (Norman 1880)	x				
Cibicides bertheloti (d'Orbigny 1839)	x				
Cibicides lobatulus (Walker and Jacob 1798)					x
Elphidium excavatum (Terquem) f. *clavata* Cushman 1930			x		
Elphidium magellanicum (Heron-Allen & Earland 1932)	x				
Hyalinea balthica (Schroeter 1783)	x				
Islandiella helenae Feyling-Hanssen & Buzas 1976				x	
Islandiella norcrossi (Cushman 1933)				x	
Melonis barleeanus (Williamson)	x				
Nonionella turgida (Williamson 1858)	x				
Nonionella iridea Heron-Allen & Earland 1932	x				
Nonionellina labradorica (Dawson 1860)		x			
Pullenia osloensis Feyling-Hanssen 1954	x				
Stainforthia concava (Höglund 1947)	x				
Stainforthia fusiformis (Williamson 1858)	x				
Planktonic foraminiferal species					
Globigerina bulloides d'Orbigny	x				
Neogloboquadrina pachyderma (Ehrenberg 1861) dextral	x				
Neogloboquadrina pachyderma (Ehrenberg 1861) sinistral				x	
Neogloboquadrina dutertrei (d'Orbigny) as P–D* intergrade	x				
Turborotalia quinqueloba (Natland 1838)		x			

* P–D intergrade is undifferentiated *N. pachyderma* and *N. dutertrei*.

in Boreal benthic species and other benthic warm-water indicators. The ratio of Arctic to total planktonic fauna is very high during this zone, showing only a slight decrease that corresponds to the rise in Boreal benthic fauna, perhaps suggesting a stratified water column.

Assemblage Zone 6, Transitional Unit: 3.02–2.26 m (10.3–9.95 ka BP).

The samples from lithofacies Ssd and Fb show a very marked change in the benthic foraminiferal fauna from the underlying pebbly, glacial-marine mud. *I. helenae* and *I. norcrossi* (up to 65%) and *N. labradorica* (up to 59%) dominate the samples, and the two glacial-marine species, *C. reniforme* and *E. excavatum* f. *clavata*, comprise 19% of the fauna, at most. The ratio of *N. pachyderma* sinistral to the total planktonic fauna is 1.0, and the planktonic foraminiferal abundances are very low.

The stratigraphically inverted age at 2.78 m on *N. labradorica* and *Islandiella* spp suggests that much of the fauna in lithofacies Ssd is reworked. However, the stratigraphically consistent radiocarbon date on *N. labradorica* at 2.52 m in lithofacies Fb indicates that a similar cold, Arctic benthic fauna occupied the shelf near the end of the Younger Dryas chronozone.

Assemblage Zone 7, Postglacial Unit: 2.23–1.63 m (9.94–9.91 ka BP).

In the earliest postglacial sediments, percentages of *E. excavatum* f. *clavata*, Boreal species, *M. barleeanus*, and *S. concava* all begin to rise. At 1.63 m, *E. excavatum* f. *clavata* and *C. reniforme* increase while the Boreal species decrease. The ratio *N. pachyderma* sinistral to the total planktonic fauna follows the trend in the benthic species, with an early decline in the ratio followed by a well-defined rise.

In Assemblage Zone 7, the increase in Boreal species and the decrease in the ratio of Arctic to total planktonic foraminifers shows that Atlantic water carried in the Irminger Current became a stronger influence on the shelf during the earliest Preboreal chronozone. A resurgence of glacial-marine species coinciding with an apparent increase in sedimentation rate may reflect either reworking of glacial-marine sediments during the early postglacial period, or a return of glacial-marine conditions during the early Preboreal. The slight increase in IRD supports the interpretation of a partial return to glacial-marine conditions, but is not conclusive.

Assemblage Zone 8, Postglacial Unit: 1.62–1.10 m (9.91–9.4 ka BP).

Boreal species rise to 87%, the ratio of Arctic to total planktonic fauna declines, and glacial-marine species disappear from the shelf. Benthic and planktonic foraminiferal concentrations rise dramatically. This assemblage marks the onset of fully postglacial marine conditions with a strong influence of warm Atlantic water in the Irminger Current on the shelf between 9.9 and 9.7 ka BP.

Discussion

Origin of the transitional unit; sedimentary evidence of a jökulhlaup

The sedimentary origin of the two-part transitional unit that separates the glacial-marine and postglacial sediments is important in the interpretation of the deglaciation of the southwestern Iceland shelf. Multiple lines of evidence (stratigraphical, seismic, sedimentological, geochemical, chronological, biostratigraphical) suggest that this unit represents a marked change in the sedimentary environment, possibly a catastrophic event.

Prior to deposition of the transitional unit, glacial ice had directly influenced the marine environment; after its deposition, the direct influence of glacial ice was largely absent. Interpretation of the seismic profiles suggests that the transitional unit was deposited in two phases: an early phase combining rain-out of sediments and sediment gravity flows, followed by a phase of debris flow deposition. In the core, the two phases interpreted from seismic profiles are represented by two distinct lithofacies; a lower, strongly stratified, very sandy unit with large dropstones, and an overlying unstratified, bioturbated, sandy unit lacking coarse IRD.

The high sand content of the transitional unit is a consequence of an abrupt influx of basaltic (basic) and rhyolitic (silicic) glass shards of Vedde Ash as well as basaltic grains derived from the fissure volcanics of the WVZ (Fig. 5). The concentration of the Vedde Ash in the sand indicates that the transitional unit cannot simply represent winnowing of the shelf. The stratigraphically reversed radiocarbon date within lithofacies Ssd indicates reworking of older foraminifera during deposition of the lower subunit.

One interpretation of the origin of the transitional unit which is consistent with all of the evidence presented is that it represents sediments deposited as a result of a catastrophic glacial outburst flood (jökulhlaup) beneath the glacier over the WVZ. Such an event could have broken up the marine ice margin and caused it to retreat onto land, removing its direct influence from the marine environment. During the earlier phase of such an event, a burst of sediment-laden meltwater and icebergs would have carried abundant sediments, including tephra shards, in suspension and in turbidity currents onto the shelf. Previously deposited shelf sediments would have been entrained as well, as evidenced by the stratigraphically reversed date within the lower subunit. A subsequent phase of debris flow deposition probably immediately followed the initial event.

Although the Vedde tephra comprises close to 50% of the tephra grains in the transitional unit, a jökulhlaup from the subglacial Katla volcano is an unlikely origin for this deposit. Faxaflói Bay is topographically isolated from Katla; a jökulhlaup from Katla would travel to the south rather than to the west into Faxaflói Bay. A more likely explanation is that Vedde Ash was deposited as air-fall tephra onto the surface of the glacial ice that was draining into Faxaflói. Coincident volcanic activity in the fissure volcanic zone produced a jökulhlaup that carried fissure volcanic materials into Faxaflói in a catastrophic event. Vedde Ash would have been passively transported on the ice during such an event. Lacasse *et al.* (1996) correlated voluminous ignimbrites found in South Iceland to the Vedde Ash eruption and indicated that this eruption may have generated pyroclastic flows and jökulhlaups that initiated sediment-gravity flows into the deep sea, suggesting that such events have been reported during approximately the same time interval.

There are uncertainties in the timing of the inferred jökulhlaup. The rhyolitic grains constitute the first occurrence Vedde Ash, which has been dated to 10.3 ka BP (Bard *et al.* 1994). However, we cannot prove that the delivery of Vedde Ash to Faxaflói Bay was by ash fall from the primary eruption. The date on *N. labradorica* from the overlying lithofacies Fb of 10.03 ± 60 ka BP is too young to represent primary deposition of Vedde Ash. In addition, lithofacies Fb is interpreted to correspond to the debris flow deposit in the transitional seismic unit. It should have been deposited rapidly and should contain reworked sediments as well. Therefore, the most conservative upper age estimate of the transitional unit is derived from the date of 9.94 ± 95 ka BP, 3 cm above the boundary between the transitional unit and the postglacial sediments. Without additional radiocarbon dates from new cores, we cannot further constrain the age of this event. We can say only that it must have occurred between 10.3 and 9.94 ka BP.

The age model for 93030-006 LCF is based on the assumption that lithofacies Ssd is contemporaneous with the Vedde Ash. This assumption is supported by the observation that synchronous, or very closely spaced in time volcanic eruptions in the WVZ and Katla are a reasonable scenario. Increased volcanic activity during the last deglaciation on Iceland has been closely linked with pressure release on magma chambers resulting from diminishing glacial loads (e.g. Sejrup *et al.* 1989; Sjøholm *et al.* 1991; Sigvaldason *et al.* 1992). Furthermore, sediment from Lake Hestvatn in South Iceland dated from the end of the Younger Dryas chronozone include both the Vedde Ash and coevally formed tephras that are chemically affiliated with intense eruption events within the WVZ (Hardardóttir *et al.* in press).

Onset of deglaciation of the shelf

Given its stratigraphic position of only about 1 m above ice-contact sediments, the basal date of 12.7 ka BP on core 93030-006 LCF puts a close constraint on the timing of deglaciation of Jökuldjúp. The basal faunal zone of the core did not have a typical 'ice proximal' assemblage. Boreal species and the slope-dwelling species, *C. neoteretis* were common, reflecting both the presence of the Irminger Current during the initial deglaciation and immigration of *C. neoteretis* onto the recently deglaciated shelf. Slight isostatic depression of the shelf may have contributed to the penetration of a deeper water mass immediately after the ice retreat. The glacial-marine species *C. reniforme* occurred in relatively low numbers, but a large percentage spike of *E. excavatum* f. *clavata* punctuates the interval, reflecting the influence of turbid meltwater delivered by the retreating ice (Hald *et al.* 1994).

Other studies show that the ice margin had retreated to coastal areas and readvanced to near the periphery of land after retreat from the LGM configuration (Ingólfsson 1988). Syvitski *et al.* (1999) noted that deglaciation must have proceeded extremely rapidly, because dates in raised marine sediments in Borgarfjördur indicate that initial deglaciation there was accomplished by 12.5 ka BP. To accomplish such rapid ice retreat, calving of the ice margin must have been the dominant ablation mode.

Although the observations in the core can be explained by rapid deglaciation by calving, they are troublesome for another reason. Most other arctic shelves had begun to retreat from their maximum LGM positions by *c.* 14.5 ka BP (e.g. Andrews & Tedesco 1993; Polyak *et al.* 1995). Directly across the Denmark Strait, the Greenland Ice Sheet had retreated rapidly from its maximum position on the shelf edge by *c.* 14.5 ka BP (Stein 1996; Smith *et al.* 1998), but retreated more slowly from the inner shelf.

We do not know whether the retreat documented in Jökuldjúp represents continuous retreat from a late Weichselian margin near the shelf break, or if it represents retreat from an intermediate position landward of the shelf break. If the former were true, then the ice sheet would have stayed at the shelf edge very late compared to other margins. Moraines mapped by Egloff & Johnson (1979) at intermediate positions on the SW Iceland shelf (Fig. 2) may have formed at the LGM, or they may represent stillstands or slight readvances during the deglaciation.

Paleoenvironments 12.7–9.4 ka BP

Core 93030-006 LCF provides a 'continuous' record of Iceland shelf paleoenvironments during the Last Termination, between 12.7 and 9.4 ka BP. In Fig. 7 we summarize the interpretations of the environmental conditions in Jökuldjúp between 12.7 and 9.4 ka BP by showing the variations in the key environmental proxies against radiocarbon age and regional and local climatic and glacial events.

The Bølling chronozone, was an overall warm interval, during which the recently deglaciated shelf was under the influence of a strong flow of Atlantic water in the Irminger Current. The strong influence of the Irminger Current was interrupted between 12.6 and 12.4 ka BP and 12.2 and 12.0 ka BP by glacial meltwater influx. The Kolluáll moraine offshore may be correlative with these features, but it is as yet undated (Syvitski *et al.* 1999). The timing of increased glacial conditions between 12.2 and 12 ka BP precedes the Older Dryas-aged Skipanes glacial event in Borgarfjördur (beginning by 12 ka BP and culminating at 11.7 ka BP). However, these events overlap if a two-sigma error on the dates is used.

Between 12.0 and 11.1 ka BP, spanning the Older Dryas and Allerød chronozones, cooler conditions reflect distal glacial-marine conditions with a weak, sporadic influence of the Irminger Current and a progressive warming of surface or near-surface waters. The glacial meltwater influence began to increase at 11.4 ka BP. The occurrence of glacial-marine sediments with boreal-arctic to arctic transitional molluscan faunas in Borgarfjördur during the Allerød chronozone *c.* 11.7 ka BP and 11 ka BP (Ingólfsson 1988) is consistent with the paleoenvironments in core 93030-006 LCF. Stratigraphy, chronology and faunal content of the Fossvogur marine sediments indicate a temporary expansion of glaciers into marine environment with elevated relative sea level in the Reykjavík region near the end of the Allerød chronozone.

Core 93030-006 LCF shows initiation of the Younger Dryas cooling at 11.14 ka BP. The glacial influence on the marine environment diminished, but cool conditions persisted, with a slight influence, or absence of Atlantic water in the Irminger Current between 11.14 and 10.5 ka BP. This cold interval corresponds well with the Skorholtsmelar event (11 to 10.3 ka BP). These results are also consistent with data from Fossvogur, SW Iceland, where glacial-marine sediments were being deposited during the late Allerød/early Younger Dryas (Sveinbjörnsdóttir *et al.* 1993; Geirsdóttir & Eiríksson 1994). Geirsdóttir & Eiriksson (1994) concluded that during the Younger Dryas (at least from 11 to 10.55 ky

BP according to the list of dates in Sveinbjörndóttir *et al.* 1993) the sediments reflect increased distance from the sediment source (i.e. glacier front) and continued marine transgression.

From 10.5 to 10.3 ka BP, the glacial influence on the shelf, including glacial meltwater, diminished. The water column was stratified, with warmer Atlantic waters penetrating onto shelf again near the seabed, but surface conditions remaining cold. The timing of the onset of subsurface warming at 10.5 ka BP is derived from the assumption that the first occurrence of Vedde Ash in the core is contemporaneous with eruption of the tephra. If this tephra were delivered closer to 10.0 ka BP, then the onset of warming would be later as well, which would be more consistent with other records of the duration of Younger Dryas cooling indicating that the Vedde Ash was erupted during a cold interval (Haflidason *et al.* 1995; Hald & Aspeli 1997). However, raised marine records from Iceland show glacier ice retreat during the latter half of the Younger Dryas (e.g. Ingólfsson 1988; Geirsdóttir & Eiriksson 1994) with a boreal–arctic molluscan fauna inhabiting the inshore areas (Eiríksson *et al.* 1997). Eiríksson *et al.* (1997) also noted an early warming during the Younger Dryas, which they attributed to an early influx of warm Atlantic water. However, in the 93030-006 LCF, the warming appears to have terminated during the inferred Jökulhlaup event in the very latest part of the Younger Dryas. In addition, recent work by Eiriksson *et al.* (2000) shows a subsurface warming at the same time on the northern Iceland shelf.

Between 10.3 and 9.94 ka BP, a jökulhlaup event beneath the glacier on the WVZ is inferred to have broken up the marine ice margin and caused it to retreat onto land, removing its direct influence from the marine environment. Arctic conditions existed on the shelf after the jökulhlaup, as indicated by the dominance of *Islandiella* spp. and Arctic to total planktonic ratios of 1.0 (Figs 6, 7).

During the early Preboreal chronozone, Atlantic water carried in the Irminger Current increased on the shelf, coinciding with a partial return to lowered salinity, glacial-marine conditions. On the basis of isotope analyses and planktonic foraminiferal assemblage data centered over the same interval in the 93030-006 LCF, Hagen (1995) reported a 6°C cooling in the Irminger Current. The concurrence of the planktonic and benthic data strengthens the evidence for a Preboreal cooling on the Iceland shelf. Geirsdóttir *et al.* (1997) indicate rapid accumulation of sediments along the southern Iceland coast during the early Preboreal in response to the retreat of glacial ice from the Búdi morainal complex. Ice retreat from the Preboreal ice margin could be recorded in Faxaflói Bay, but the data from the core are not conclusive.

The onset of postglacial marine conditions with a strong influence of warm Atlantic water in the Irminger Current on the shelf began by 9.7 ka BP.

Conclusions

1. Jökuldjúp was deglaciated at *c.* 12.7 ka BP. The rapid deglaciation was probably accomplished by calving of the ice margin.
2. Between 12.7 and 11.1 ka BP, the shelf was under the competing influences of Atlantic water inflow and influx of sediment-laden glacial meltwater from an ice margin terminating on the inner shelf or in the fjords.
3. Younger Dryas cooling was initiated at *c.* 11.1 ka BP, as reflected by little or no influence of warm Atlantic water. According to the chronology adopted in this article, cooling continued until at least 10.5 ka BP, when subsurface penetration of Atlantic waters produced a slight renewed warming.
4. The end of glacial-marine sedimentation coincides with the first occurrence of Vedde Ash within a transitional unit, interpreted as a jökulhlaup deposit. The inferred jökulhlaup would have emanated from beneath the glacier over the WVZ and is envisioned as playing a strong role in the retreat of the glacier ice from the marine environment. Given the uncertainties in dating the transitional unit, this event occurred sometime between *c.* 10.3 and 9.94 ka BP.
5. The onset of postglacial marine sedimentation occurred along with increasing evidence of Atlantic water *c.* 9.94 ^{14}C ka BP and was interrupted by a short-lived Preboreal cooling of the Irminger Current *c.* 9.91 ^{14}C ka BP. Postglacial marine conditions characterized by a strong influence of warm Atlantic water in the Irminger Current began by 9.7 ka BP.

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